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CHAPTER VIII

THE PROTECTION OF THE PUBLIC:- SHELTERS

8.1 General considerations in shelter provision

The problem of the protection of the public from an attack can clearly be tackled from two directions:-

(i) by removing people from areas subject to attack, and
(ii) by providing them with accommodation within which they will be reasonably safe, even in an area which suffers heavy bombardment.

Obviously the first solution, when practicable, is much to be preferred. There is no doubt that thousands of lives were saved during the war by evacuation. But the solution has only a limited application. The work of the country must go on, and the workers must not only congregate in large numbers during working hours, but must also live relatively near their work, that is to say, in or near those areas which will attract attack. When the production of the country is concentrated, as is largely the case, in a few areas, the task of the attacker is rendered much easier, and in the colossal amalgam of industry, transport and commerce which is represented by a city like London, he can drop bombs almost at random knowing that few will be, from his point of view, entirely wasted.

The situation therefore arises in which people must be protected against an attack directed not primarily against them, but against the essential life of the country. The attempt may be made to destroy the actual means of production, the factories, by blast or fragmentation, to dislocate transport by blocking roads and railways by the craters of delay-fuzed bombs, or to force the workers to leave their work by destroying, usually by the use of fire, the dwellings in which they live. Against all these agencies of attack protection must be provided, and, if this is done, it will be found that to a very large extent, the people have also been protected against an attack, if one should be launched, directed primarily against them.

Naturally a great part of the effort of R. & E. Department was directed towards the solution of this problem, particularly in the earlier years of the war, and it is impossible in a single chapter to refer to all this work. We have therefore elected to deal in some detail with the theory of shelter performance, and with the requirements which must be met in any satisfactory shelter, but to give only a brief description, with drawings, of the standard types of shelter in use. Accordingly, in addition to the references which we make from time to time in the text, we have included at the end of this chapter a bibliography of the shelter problem.

The scientific problem of shelter provision has two aspects, only one of which is structural in character: the other is statistical, and an adequate treatment of the structural problem is only possible if the statistical background is appreciated. We shall consider at some length the fundamental statistics of the problem, since, although the technique will seem to the statistician to be of the most rudimentary character, it may be that to some engineers it will be less familiar.

8.2 The concept of "vulnerable area"

Consider any one individual in the area under bombardment. If he is hit by a bomb it may be assumed that he becomes a casualty, but if the bomb drops a little distance away, he may escape harm. Suppose that of bombs dropping between distance r and distance r + dr a number n injure him, while he escapes injury on m occasions. Suppose moreover, with praiseworthy persistence, he remains at his post unmoved until the numbers n and m have both become large*. Then the probability p_r of his being injured by one bomb falling at distance r from him is defined as $\frac{n}{n+m}$. (In general, the probability of any event is defined as the limit of the ratio of the number of times the event occurs, to the number of "trials", i.e. the number of occasions on which it might occur, as the latter becomes infinite). Now, if the fall of bombs round the individual in question is "random" that

* It is assumed that the fall of any one bomb does not affect his chance of being injured by subsequent ones.

is to say, if any unit of area is as likely to receive a bomb as any other unit, then the total probability of his being injured by one bomb falling within an area A which is large compared with the area in which it must fall in order to injure him, is given by P in -

$$AP = \int_0^\infty 2 r p_r \, dr \qquad \text{..... (8.1)}$$

It will be seen that the quantity on the right-hand side of the equation has the dimensions of an area. This area is the "vulnerable area" for the individual concerned. It can be defined verbally as follows:- the "vulnerable area" for an individual under specified conditions is an area such that if all bombs falling within it caused injuries, and all bombs outside were harmless, then the total risk to which the individual is exposed would be the same as it is under the specified conditions.

So far we have considered the vulnerable area from the point of view of the individual. It is also possible to consider it from the point of view of the bomb. (Strictly, in this case it should not be called "vulnerable area", but "danger area". The same term is, however, in common use in both senses, and no confusion need arise if the distinction between the two is borne in mind). Here we assume that of (n + m) individuals situated between radius r and radius r + dr from the bomb n are injured and m are uninjured. The probability of injury p_r is therefore the limiting value of n/n + m as n + m becomes large, and if the population density is N people per unit area, the average number of casualties occurring between r and r + dr is -

$$N \,.\, 2\pi r p_r \, dr$$

Thus the average total number of casualties is -

$$2\pi N \int_0^\infty r p_r \, dr$$

which is equal to the vulnerable area times the population density.

Thus, given the vulnerable area, it is easy to calculate the average number of casualties which would be caused by an attack of specified density on a given population. Suppose that in a given district of area A there are N people who are all equally exposed to risk, all having the same vulnerable area V. Then if n bombs are dropped on the area, the expected number of casualties produced is -

$$C = \frac{nNV}{A} \qquad \text{..... (8.2)}$$

provided that the product $\frac{NV}{A}$ is much smaller than unity .

Clearly, while the definition in equation (8.1) does not lend itself to experimental measurement - the individual is in fact never exposed in unchanged circumstances to numerous bombs - we can conveniently determine the vulnerable area of a given weapon either by a detailed survey of individual incidents, or by a mass count of casualties from a specified area using equation (8.2). If we adopt the former method, we select an incident, or a number of incidents involving the same type of bomb, in which a large number of persons were exposed to risk under comparable conditions (e.g. in houses, or in the open); we then divide the area round each bomb into a number of annuli bounded by circles of specified radius, and we determine the number of persons injured and the number uninjured in each annular ring thus formed; hence we deduce the probability p of injury at distance r from the bomb. A simple numerical integration then gives the vulnerable area. In the latter method, we enumerate the number of bombs falling in a specified area, the number of persons exposed to risk under the specified conditions in this area, and the number of casualties caused among them. We then deduce the vulnerable area from equation (8.2). This method is only applicable in cases where all the bombs in a given area are of a specified type, and the proportion of the people exposed under various conditions (e.g. in houses, in the open, in shelters, etc.,) is known, as well as the number of casualties occurring in each situation.

Yet another proviso must be made if the equation (8.2) is to be applied direct to the determination of vulnerable area. The product of the number of bombs N, and the probability of injury from any one bomb P must be small compared with unity i.e. the total probability of any one individual becoming a casualty must be small. Fortunately, there is no direct experience in the United Kingdom of attacks so concentrated that this condition becomes untrue. Nevertheless, it is useful to examine from the theoretical standpoint, what happens under conditions of extreme concentration.

The probability that a given individual is injured by one specified bomb is p. The probability that he is not injured by this bomb is $(1 - p)$, let us say q, so -

$$p + q = 1$$

Then the probability that he is not injured by any one of N bombs is q^N, since, if the scatter of bombs is random, all these probabilities are mutually independent, and the probability of all the events happening, i.e. of him surviving all bombs, is the product of the probabilities of each independent event.

....

Similarly, the probability that he is injured by the first bomb, but by no other is pq^{N-1}. And the same is true of the second bomb, or the third, or any other one bomb. Now the probability of at least one of a series of events happening, is the sum of the probabilities of independent events. Thus the probability that an individual will be injured by one and one bomb only is

$$Npq^{N-1}$$

Similarly, it can be argued that the probability of his being injured by two and only two bombs is

$$\tfrac{1}{2} N(N-1)\, p^2 q^{N-2}$$

and so on, until finally the probability that any individual will be injured by every bomb is p^N.

It will be seen that the chances of injury by all bombs, by all bombs but one, by all bombs but two, are respectively the first, second and third terms in a binomial expansion

$$(p + q)^N = p^N + Np^{N-1}q + \tfrac{1}{2}N(N-1)p^{N-2}q^2 \ldots\ldots Npq^{n-1} + q^n$$

The total chance of at least one injury is $1 - q^N$ and this is the quantity which is usually required. Indeed the remaining coefficients have little meaning, since the probabilities referred to are not independent, a man once injured is likely to change his circumstances to others in which the risk is either greater or less.

If an area A is bombarded by N missiles each having vulnerable area (danger area) V the total probability of injury for any individual is therefore -

$$1 - \left(1 - \frac{V}{A}\right)^N$$

and if there are n individuals exposed to risk in the area, the expected number of casualties is -

$$C = n\left\{1 - \left(1 - \frac{V}{A}\right)^N\right\} \qquad \ldots\ldots\ldots\ldots (8.3)$$

It will be seen that for the case when VN is small compared with A, this formula approximates to equation (8.2). A second more accurate approximation to equation (8.3) is provided by Poisson's exponential formula, which in our notation, replaces equation (8.3) by -

$$C = n\left\{1 - e^{-\frac{NV}{A}}\right\} \qquad \ldots\ldots\ldots\ldots (8.4)$$

It can easily be shown by expanding these two forms as infinite series, that the substitution of (8.4) for (8.3) corresponds to the suppression of terms of the order $\frac{V^2}{A^2}$, $\frac{V^3}{A^3}$, etc., in comparison with $\frac{NV^2}{A^2}$, $\frac{NV^3}{A^3}$, etc. It is

thus very accurate, when as is usually the case, the number of bombs N is very large. In fact, equation (8.4) has been generally used for theoretical prediction of bombing results in the present war, and there is no doubt that, for most purposes, it is the most convenient form.

In fact the casualties occurring in similar raids on similar targets will show large variations due to chance effects. The "expected number" of casualties given in the equation above is only the number which is expected to occur on the average over a very large number of similar raids: the number of casualties occurring in any one raid cannot be predicted with accuracy, except within limits "the confidence limits" for the prediction. It is impossible to say that the number of casualties in a given raid will be C_m, or even that it will be between $C_{min.}$ and $C_{max.}$ What can be said however, is that in n similar raids, the casualties on m occasions will fall between specified limits C_L and C_s*.

It is not necessary here to describe the statistical techniques by which confidence limits can be determined; these can be found in the standard text-books on the subject. Our intention is only to emphasize first that predictions based on the concept of vulnerable area are averages, to which reality will only approximate when the "trial" is repeated a large number of times; and secondly that they show this property with predictions based on measurements of any other physical quantity.

In the discussion which follows the concept of "vulnerable area" will be used throughout as measure of the efficiency of a shelter against a given type of attack. Strictly this "vulnerable area" should be a measure of the risks run by an individual in the specified type of shelter. It is impracticable, however, to measure this quantity under the controlled conditions of experiment. For this reason, it has become customary to apply the term "vulnerable area" in a loose sense to the shelter itself, defining it as the area in which a bomb must fall in order to damage the shelter so severely that a specified proportion (say one-half) of the occupants become casualties. In the detailed discussion of the various shelter types in the paragraphs below, statistics relating the damage to the shelter to the proportion of casualties caused will be given when possible, and hence the degree of damage associated with 50 per cent casualties can be determined. The area within which a bomb must fall in order to do damage of this character can then be determined experimentally with vacant shelters and thus a judgement can be made of the risks to the occupants, if they had been present.

8.3 Causation of casualties

We have now to examine in detail the various ways in which bombs can kill and injure people. In the list below we have set out the principal causes of casualties✗, as far as possible in order of importance, i.e. in order of the frequency with which they occur -

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* It may seem that statements of this sort differ in kind from the statements with which engineers are familiarly concerned. It is suggested however, that the difference is illusory. The statement "Young's modulus for steel is 30×10^6 lb./sq.in." is a commonplace but untrue. The true statement of the fact which it summarizes is "If n steel specimens are tested, Young's modulus will be found, to lie between (say) 29.5×10^6 lb./sq.in. and 30.5×10^6 lb./sq.in. on m occasions".

✗ These mechanisms of injury attracted very little attention before the present war, but since 1939 a series of studies have been carried out by the Oxford casualty survey under Professor S. Zuckerman, and it has been possible to collect quantitative information on the conditions under which serious injuries are caused. We summarize in the text the principal conclusions derived, while referring to the original papers for their experimental foundation.

(a) Burial, asphyxiation and secondary causes such as fire and flooding which may prevent the escape of people trapped by the collapse of buildings

The exact degree of confinement under which asphyxiation can take place is not usually a factor of importance in shelter design. As far as is known no cases of casualties due to this cause in shelters inside buildings have occurred except when the shelter itself has collapsed. The minimum volume of such shelters is fixed by considerations of convenience rather than by the supply of oxygen necessary in cases where the shelter is cut off from the outside air completely by the collapse of debris.

(b) Injuries due to the impact of missiles, masonry, debris, etc.

We deal next with injuries resulting from the impact of the relatively slow-moving missiles which are produced by the demolition of buildings, or in the formation of craters by the explosion of bombs in the ground. The velocity of such projectiles will not in general exceed about 50 - 100 ft./sec. and they will not in general inflict wounds by penetration. They fall roughly into two classes, the "hard" strikers, such as masonry fragments of concrete or rock, etc., which are not likely to be deformed by the impact and which were in the experimental work[1], represented by brass cylinders; and the "soft" strikers, like soft clay, mud, etc., which were represented by plasticine, and which undoubtedly change their shape substantially on striking. It was found that, in both cases, the damage caused could be closely correlated with the kinetic energy of the projectile but that, while for the "hard" striker, the energy necessary to cause an "incapacitating" injury in 50 per cent of the cases tried was only 30 ft./lb. For the "soft" striker, it was no less than 1,800 ft./lb. Of course, these figures are subject to substantial variations according to the part of the body struck, according to the degree of protection afforded by, for example, a hat or helmet, and also from individual to individual under comparable conditions. A missile cannot be said to be harmless with any degree of confidence unless its energy level does not rise about 1/20th of these figures.

(c) Injuries due to the injured man himself being thrown about by blast or earthshock

Only a comparatively few experiments have been performed on this subject[2], and there is no doubt that much depends on the precise nature of the impact suffered. Numerous cases are recorded of survivals without serious injury in falls up to 50 ft. while, in other cases people have suffered severely in falls of no more than two or three feet. It has been shown that the threshold for ankle injuries due to sudden upward movement, such as happens when a man stands very near the edge of the crater of a buried bomb, occurs when the impulsive velocity is about 12 ft./sec. and it is believed that this figure is fairly representative for other types of impact. It therefore seems probable that if a shelter is projected at velocities higher than this, injuries may be caused to the occupants, even if the shelter is structurally undamaged, and that the frequency and severity of the injuries will increase as the velocity rises more and more above the threshold. We shall find that this criterion imposes a serious limitation on the degree to which certain types of small shelter can be usefully strengthened.

(d) Fragmentation injuries[3]

Numerous experiments have been carried out with a view to determining the relation between the mass and velocity of a bomb fragment and its power to cause injury. It is believed that a serious injury will be caused provided that one of a number of vital organs are penetrated. It follows that the threshold of injury is associated only with the fragment penetration, and not directly with its mass. No doubt the larger fragments cause the more dangerous injuries; but, if we are concerned

only with numbers of persons incapacitated, we can base our calculations solely on the fragments having more than a specified penetrating power, regardless of their mass. It also follows that the area in which an incapacitating injury can be inflicted is much below the total presented area of the body. In the paper quoted[3], the effective "vulnerable area" x to small fragments is estimated at about 2.8 sq.ft. in an average case.

The relation between mass m, velocity v and penetration p into a material having similar resistant properties to human tissue is found to be -

$$p = kvm^{0.4} \qquad \text{......... (8.5)}$$

A fragment weighing .0018 oz. striking the vulnerable area at a velocity of 1,200 ft./sec. is found to inflict an incapacitating injury in 10 per cent of cases. If the velocity is 2,700 ft./sec. this ratio rises to 50 percent, and if the fragment is travelling at 4,600 ft./sec. it will incapacitate in all but 10 per cent of cases. The corresponding velocities for other weights of fragments can be deduced from equation (8.5), but this process cannot be applied to very large fragments (say 1 oz. or larger) without reserve, since new causes of incapacitation, such as shock, gross superficial injuries, etc., may be at work in these cases. It is worth noting, however, that if the equation were stretched to cover fragments of mass 1 lb. the velocity deduced for 50 per cent incapacitation would be about 70 ft./sec. corresponding to a kinetic energy of 77 ft./lb. which is of the same order as the kinetic energy as given in (b) above for the "hard" striker.

It must be realized that these criteria, which were derived in the first place largely for military purposes, tend to deal only with injuries which will certainly be incapacitating, i.e. which will certainly necessitate medical attention over a period of time. Numerous minor injuries, and also no doubt some serious ones, will be caused by even smaller fragments travelling at lower velocities.

From the defensive point of view, these estimates are of importance in the problem of body armour, which is outside the scope of the present work, and also because they emphasize clearly enough the consequences of any failure to provide fragment-proof protection in shelters. If only relatively large fragments were to be feared the probability of casualties at a moderate distance from a bomb, even under unprotected conditions, would be small, but, if as is actually the case, fragments down to a few milligrammes are to be reckoned with (and from modern M.C. and H.C. bombs these will be by far the most numerous) then a single bomb will produce many thousands of potentially dangerous fragments, and the probability of a man being hit by at least one will be appreciable even at a considerable distance.

(e) Injuries due to flying glass

These injuries differ only from those due to other secondary missiles (paragraph 8.3(b)) in that glass is commonly exposed to blast in thin sheets of small mass per unit area, and thus is particularly liable to be projected at high velocity. Moreover, it commonly breaks up into splinters of a particularly damaging shape which for a given mass and velocity are capable of much greater penetration than the ordinary irregularly shaped bomb fragment. For this reason, particular attention has been paid to the elimination of glass or to the prevention of flying splinters. A discussion of the subject will be found in Chapter XII. For the present purpose it is sufficient to say that flying glass must

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x Vulnerable area in this sense, i.e. the area of the body within which a serious wound can be inflicted, must not be confused with the statistical meaning of the phrase.

clearly be excluded from all shelter provision. It should be remarked that to do so it is necessary not only to prevent flying glass from entering the shelter, but also to ensure that there are no glass screens, partitions or other objects within the shelter, since these may be shattered and projected at a dangerous velocity by a blast wave far less intense than that required to cause direct injury to the occupants.

(f) Direct blast injuries[4]

Many accounts have been given (and in some cases these have become legendary) of instances in which fatalities have occurred without visible injury at some considerable distance from an explosion, and these have usually been attributed to mysterious powers of blast. Perhaps such mysterious deaths have occurred, some of them no doubt from natural causes, but it is now decisively proved that they cannot have been due to blast. Many experiments have shown that there is only one mechanism by which the blast wave can cause injury, that is, by direct impact on the chest wall, which, if the intensity of the wave is very great causes lung injuries producing symptoms similar to those encountered in Pneumonia. A minor injury which often occurs under less severe conditions is the rupture of the eardrums.

It is found that the extent of the injury inflicted in this way can be correlated direct with the maximum pressure in the blast wave. Its duration is without effect.

The pressures necessary to cause a specified degree of injury in an average case are approximately as follows:-[4]

	(lb./sq.in.)
Death	370-470
Serious injury	100
Slight injury (usually ruptured eardrums)	15

In the circumstances in which men are repeatedly exposed to blast, as for example in the firing of large naval guns, or land artillery, it is usually considered that pressures up to 5 lb./sq.in. are harmless particularly if some form of protection to the ears is provided.

It follows from the above figures that serious injuries due to blast, unassisted by other causes, are extremely rare. The pressure of 100 lb./sq.in. needed to cause such injuries will occur only up to the edge of the flame zone, where anyone in the open will be exposed to a very high risk of injury from one or more of the sources detailed above. So far as is known, no casualty from direct blast effect alone has ever occurred inside a shelter as a result of an explosion outside.

8.4 Shelter occupancy

In the preceding paragraph we have laid down the mechanical requirements for the shelter - the various phenomena against which it must be capable of protecting its occupants. There are, however, other considerations which affect the design, and which may be grouped under two heads - comfort and accessibility. If an adequate standard is not achieved under these two heads, the shelter will fail in its purpose, whether the standard of protection offered is good or bad, because it will never be occupied.

In the present war, attacks against this country have been of two kinds -

(a) Long duration night attacks

In general adequate warning of these attacks was always given, and the immediate accessibility of the shelter was less important than provision for sleeping, adequate ventilation, etc.

(b) Short duration day attacks (e.g. attacks by flying bombs)

Warning for such attacks is necessarily short*. The essential

* In the case of weapons of the V.2 rocket type no warning has been possible in this war, but it is not unlikely that the future developments of radio-location technique might make possible a brief warning for even the highest velocity missiles.

requirement is that the shelter should be immediately accessible. Clearly no policy involving the provision of a small number of large shelters can meet this requirement.

In estimating the relative efficiency of various shelter types, we take account of these considerations by introducing an "occupancy" factor. Suppose that the vulnerable area for a person taking shelter is V_s and for a person not taking shelter is V_n. Then if p per cent of the people for whom the shelter was intended do in fact occupy (on the average over a number of raids) the mean vulnerable area for these people is -

$$p\,V_s + (1 - p)V_n$$

and it is this quantity rather than the actual vulnerable area V_s of the shelter itself which should be regarded as giving the measure of efficiency.

The numerical value of the percentage occupancy p depends of course on many factors such as the weight of attack, the state of public morale, etc. We are here interested only in relative values as between different types of shelter. The figures given below, for example are estimates of occupancy during a typical night raid during the period 1940-41[5]:-

Type of shelter	Percentage of population occupying shelter
Interior (Morrison or protected room type)	75 - 80
Exterior domestic shelter (Anderson or domestic surface type)	50
Small public shelter (surface communal or trench type)	30

It may be that in these cases the figures will also cover fairly well raids of the short-duration day type. If, however, we included the large public shelter, such as the deep tunnel shelters in London, the occupancy figure would be very high for a night raid, but very low (owing to inaccessibility) when the time of warning was short.

8.5 The main shelter types

In the brief description of the main shelter types which follows, we shall attempt as far as possible to follow the lines of paragraph 8.3 and enumerate the design requirements in order that each of the causes of injury there listed may be satisfactorily resisted. Where possible, we shall give results derived from experience in the actual raids. In many cases, however, a sufficient volume of experience to give by itself the required results is not available, and our observations will be based on general or experimental grounds, confirmed where possible by actual raid experience.

(i) The trench shelter

If a shelter is constructed below, or partly below the surface of the ground and covered with several feet of earth, the earth itself will provide good protection against blast and fragmentation from anything but a direct hit, and by making the area of the shelter small, the probability of a direct hit can be made almost trivial. Clearly if the roof of the trench is reasonably substantial flying debris can also be excluded. The chief risks therefore which remain are:-

(a) that the shelter will be collapsed by earthshock,

(b) that the people will be injured by being thrown about by earthshock in the interior of the shelter.

Clearly it is useless to attempt to construct a rigid trench lining capable of resisting the impulses imparted by earthshock to a rigid underground structure. If such a shelter were constructed, it would be much better to place it on the surface, where it would be more than capable of resisting the smaller blast

impulse from a surface burst bomb at a similar distance. Instead use must be made of the fact that, due to the mass and rigidity of the medium, earth-shock can impart only a limited displacement and velocity to an obstacle offering little resistance. The essential feature of trench linings must therefore be flexibility, i.e. the lining must be capable of being distorted, at least by several inches, without failing to perform its function of retaining the earth, and without permitting any debris either or earth or parts of the lining material to be precipitated into the trench. Such distortion, provided it is not so large that the contents of the shelter - seating, bunks, etc., are liable to crush the occupants, rarely causes serious injury.

Satisfactory linings have been designed in a variety of different materials - in timber, in corrugated steel and in reinforced concrete, either in situ or precast. In the latter case however, particular care must be taken to ensure that the precast units cannot be thrown into the trench if the supporting frame is badly distorted. An obvious means which might be adopted for reducing the earthshock on the side of a trench shelter is the construction of a guard trench of the kind considered in Chapter IV. For example, a space might be left vacant between the earth and the shelter wall proper. In fact the procedure is less efficacious than might be expected. A ductile trench lining stands up very well, unless it is within the crater area. There is therefore only a very small zone near the crater lip in which a guard trench can effect any substantial improvement. On the other hand, the provision of a guard trench, which will probably have to be revetted, will substantially increase the cost, and a shelter with a trench cut immediately beside it becomes much more vulnerable to blast or fragmentation.

(ii) The Anderson shelter (Fig. 8.1)

The Anderson shelter is, of course, simply a very small covered trench shelter in which the earth is retained by a corrugated steel arch held in place by light R.S. sections. Very large numbers of these shelters have been used in Great Britain and there is considerable experience of their behaviour. This experience indicates that, as expected, in a properly constructed and covered shelter few casualties occur except when the shelter itself is seriously damaged. If, for example, we categorize damage as follows:-

Category		
A1	Shelter totally destroyed	"heavily damaged"
A2	Shelter very badly distorted	
A3	End sheets removed, and/or moderate distortion of arch	"slightly damaged"
A4	Minor damage including reduction of earth cover	

We can relate the number of casualties occurring with the type of damage. This has been done for a group of 700 Anderson shelters which were attacked by flying bombs exploding within 170 ft. It is necessary to distinguish between those shelters which had (as all of them should have had) a baffle consisting of a brick wall or earth bank opposite the door to prevent the entrance of fragments or debris, and those in which the entrance was unprotected.

TABLE 8.1

DAMAGE AND CASUALTIES FOR ANDERSON SHELTERS[6]

Grade of damage	** Average circle radius (ft.)	Number of shelters studied	Casualty data (Shelters with complete data)							
			No.	Total number of casualties			Total number of occupants	Percentage of casualties		
				K*	S/I*	L/I*		K	K + S/I	K+S/I+L/I
All shelters -										
A1	15	13	13	5	1	0	6	83.3	100	100
A2	24	14	12	3	6	2	19	15.8	47.4	58.0
A3	39	24	15	2	6	6	28	7.1	28.6	50.0
A4	66	71	57	1	5	5	71	1.4	8.5	15.5
Shelters without baffles -										
A1	15	10	10	5	1	0	6	83.3	100	100
A2	24	10	8	3	3	2	11	27.2	54.5	72.7
A3	39	16	10	2	4	5	18	11.1	33.3	61.1
A4	67	52	41	1	5	4	62	1.6	9.7	16.1
Shelters with baffles -										
A1	15	3	3	0	0	0	0	-	-	-
A2	24	4	4	0	3	0	8	0	37.5	37.5
A3	39	8	5	0	2	1	10	0	20.0	30.0
A4	72	19	16	0	0	1	9	0	0	11.1

* The casualty classification is as follows:- K - killed. S/I - Seriously injured and detained in hospital. L/I - Slightly injured - received medical attention but not detained in hospital.

**The "average circle" radius is defined as the distance such that the number of shelters undamaged within a circle of this radius is equal to the number damaged outside the circle. It corresponds closely to the "vulnerable area" but is easier to compute.

The vulnerable area, as defined in equation (8.1) can be readily computed from these results, if we replace the integral in that equation by an arithmetic summation of the areas of damage times the probability of injury in each area. Fixing attention on the totals of killed and seriously injured we find the following figures -

	Vulnerable area K + S/I
All shelters	2,830 sq.ft.
Shelters without baffles only	3,200 sq.ft.
Shelters with baffles only	1,720 sq.ft.

Now the average distance at which the shelter was heavily damaged as from Table 8.1 was 24 ft., corresponding to an area $\pi \times 24^2$: 1,800 sq.ft. approx. We note that for a correctly constructed and baffled shelter the vulnerable area for serious casualties is very nearly the same as that for heavy damage to the shelter. We can use this comparison to estimate the casualty rate likely to be caused by other weapons whose effect on the structure is known, although incidents of damage to occupied shelters may be lacking.

As a standard of comparison we may here quote similar results for casualties in flying bomb attack on ordinary 2-storey brick houses, of the terraced or semi-detached type. The damage classification in the case being as follows:-

A damage - Completely demolished, less than 25% of external walls standing
B damage - Partially demolished, at least 25% of external walls demolished
C_b damage - Uninhabitable and too seriously damaged to be repaired in wartime
C_a damage - Uninhabitable but capable of rapid repair
D damage - Habitable but badly needing repair.

Table 8.2 then gives results comparable with those in Table 8.1.

TABLE 8.2

DAMAGE AND CASUALTIES FOR HOUSES

Grade of damage	Average circle radius (ft.)	No. of houses studied	Casualty data							
			No.	Total number of casualties			Total No. of occupants	Percentage of casualties		
				K	S/I	L/I		K	K + S/I	K + S/I + L/I
A	77	206	191	76	63	20	323	23.5	42.6	48.8
B	115	172	146	7	29	22	257	2.7	14.0	22.6
C_b	156*	299	282	0	30	19	326	0	9.2	15.0
C_a	-	173	158	0	4	4	182	0	2.2	4.4
D	-	44	43	0	0	0	45	0	0	0

* This value is an underestimate owing to the restriction of the zone of investigation to a distance of 170 ft. from the explosion. C_a and D radii were not measureable for the same reason.

Following the same procedure as before, we find, for killed and seriously injured taken together, the vulnerable area about 16,000 sq.ft. or more than nine times that for the properly protected Anderson shelter.

The flying bomb was of course a blast weapon, i.e. it always exploded on the surface without penetration. As such, it was equivalent to an H.C. bomb of charge-weight ratio 75 per cent and charge-weight (RDX/TNT) about 1,050 lb. and accordingly we may estimate the vulnerable area of the properly protected Anderson shelter as no more than 2,750 sq.ft. per ton of bombs of this type. But, as we remarked when considering trenches in general, any sub-surface shelter cannot readily be attacked by blast weapons; the main threat is from the delay-fuzed penetrating bomb.

Direct evidence as to the casualties produced by such bombs in Anderson shelters is scanty, due partly to the difficulty of identifying the bombs responsible for specific incidents in raids in which several sizes of bomb variously fuzed were used simultaneously, and partly to the fact that in the early part of the war the system for the collection of the required information was not fully developed, while more recently, the penetrating bomb has more and more been superseded by blast weapons. It is possible, however, to relate damage to the shelter directly with the crater size of the bomb causing the damage, and some results obtained in this way are shown in Fig. 8.2.** From this diagram we can see that the vulnerable area for "heavy damage" from penetrating bombs is about 1.6 times the crater area. The average crater area for (say 50 kg. bombs fuzed 1/40 sec. delay or longer is about 180 sq.ft. (weighting the areas for various types of soil in the proportions in which they have in fact occurred); so that we may estimate the vulnerable area (killed or seriously injured) as approximately 290 sq.ft. for this type of bomb,* giving the vulnerable area per ton 5,800 sq.ft.

* In Reference 7 Professor S. Zuckerman found that the vulnerable area for the occupants of a group of small shelters (mostly Andersons) was only 270 sq.ft. but some of his data may have involved non-penetrating bombs. In the same paper, he shows that the corresponding figure for people in houses is 1,430 sq.ft. about 5-6 times as great. In a later paper R.E.N.182 "A comparison of the number of casualties caused by German bombs of different sizes", Professor Zuckerman found that the vulnerable area against the 50 kg. for persons in Anderson shelters was no more than 126 sq.ft. compared with 810 sq.ft. for persons in houses. Note that although these figures are much reduced, no doubt as a consequence of the increased use of instantaneous fuzes in the raids studied, the ratio between the two remains about the same as before.

** Fig. 8.2 not reproduced.

Other larger types of trench shelter will clearly be more vulnerable due to the increased risk of a direct hit, and to the fact that many of the lining materials used were less capable of distortion without rupture than the corrugated steel of the Anderson.

(iii) The surface shelter (Figs. 8.3 and 8.4)

The public surface shelter as originally designed was intended for use in streets, factories, etc., where trenches were not appropriate, due to the unfavourable nature of the ground or other causes. It was thought before the war that the main risk to be contended was that from fragmentation, and the prime requirement was therefore to make the walls fragment-proof. In fact, the principal risk arises from the collapse of a shelter as a result of blast or earthshock, and if these risks are adequately met, the fragmentation risk will be negligible.

The standard of protection aimed at was also much lower than that subsequently achieved. The earliest surface shelters were designed to be proof against blast and fragmentation from a 500 lb. bomb (TNT filled) at 50 ft. and so they were. But it was afterwards found to be possible to reduce this distance to 15 ft. i.e. to nearly the standard of protection afforded by the Anderson shelter. Owing to its larger plan area, it was necessary for the surface shelter to be proof against a near-miss even closer than that required to damage an Anderson, in order to give a comparable degree of protection.

At this distance the shelter had to be proof -

(a) against the blast and fragmentation from a surface burst-bomb;

(b) against the earthshock from a delay-fuzed bomb, and in addition,

(c) the velocity with which it was displaced by earthshock had to be below the critical velocity for injury laid down in paragraph 8.3.

We have already in Chapter VII discussed in detail the problem of the design of wall panels against blast. A shelter wall does not of course differ from any other in this respect so it is not necessary to recapitulate the calculations given in that chapter.

The conclusion reached is that walls of thickness $13\frac{1}{2}$ in. for brick or 12 in. for concrete reinforced in each case against earthshock in the manner shown in Figs. 8.3 and 8.4 are satisfactory from the point of blast. It is also obvious that the performance will be improved if the shelter is allowed to slide freely on its foundation, thus absorbing some part of the blast energy. We have also noted that these walls are virtually proof against fragmentation.

We must, however, contemplate a form of failure which has not been covered by the fundamental investigations in the earlier chapters - the risk that the shelter may disintegrate either as a result of the original earthshock or more probably as a result of the impact which occurs when the shelter strikes the ground again after being projected through the air.

The earlier unreinforced surface shelters were particularly liable to collapse in this way, and a large part of the full-scale experimental work carried out by R. & E. Department in the early part of the war was directed towards determining a design which would not collapse under severe earthshock conditions, and also to devising means whereby the original unreinforced types could be strengthened up to the required standard.

A considerable number of full-scale tests were carried out with this end in view, a typical layout being that shown in Fig. 8.5. The designers were, of course, throughout handicapped by the necessity for extreme economy in the use of steel, which was, at that time, in very short supply, and in considering the designs which are shown as Fig. 8.3 and Fig. 8.4 it must be remembered that these forms were considered the best that could be done <u>with the amount of steel available.</u>

The technique of design for these conditions had to a great extent to be improvised. The remarks made in chapter VII with regard to the treatment of a "one-life" structure, and with regard to the consideration of ultimate strength rather than elastic limit, of course holds good in this context. But it is not immediately apparent how estimates can be made of the forces disintegrating the shelter, and thus of the strength necessary to hold it together. A means of approach to this problem of the measurement of the disintegrating forces was found in cine-photography. A series of photographs were taken at a moderately high speed (say 200 frames per second), of the process of disintegration of an unreinforced shelter under the specified conditions. The velocities with which the various parts scattered could then be measured from the film, and hence an estimate of the disintegrating impulses could be obtained.

One such photograph shown in Fig. 8.5a illustrates the way in which an ordinary rectangular brick shelter with reinforced concrete slab roof and floor breaks up and is demolished by a 500 lb. bomb buried 12 ft. 6 in. at 15 ft. from the shelter wall horizontally*. This photograph and others like it illustrate clearly enough what the task of the designer is -

(a) the separation of floor, roof and walls, as a result of "knock-on" effect must be prevented,

(b) the shelter must not be allowed to "fold up", i.e. to assume the form of an elongated parallelogram.

It is found that the forces necessary to prevent the separation of the various elements of the shelter are not large. A very small percentage of steel reinforcement (as little as 0.06 per cent by volume has been used), if carried continuously from the floor through the walls and into the roof, is sufficient to keep the whole structure together. When a very low percentage reinforcement is used, however, it is usual to provide cross-walls at intervals along the shelter length, as shown in Fig. 8.4, with a view to stiffening the section, and preventing "folding up". The floor, which was omitted in some of the earlier types, is almost a necessity for the same reason. Photograph 8.7, taken under the same conditions as 8.5a, illustrates the success of these measures.

The comparatively low percentage reinforcement necessary to keep the shelter together can be easily demonstrated by a calculation as follows:-

Suppose that an unreinforced shelter is tested under the specified conditions, and the maximum relative velocity of roof and walls is measured photographically and found to be 5 ft./sec. in a shelter of area 30 ft. x 8 ft. having walls 1 ft thick[8]. Then the kinetic energy of the roof, assumed 5 in. thick, and of density 144 lb./cu.ft. is

$$\frac{60 \times 25}{64} \quad \text{ft. lb./sq.ft.}$$

In this plan there are 72 ft. of wall supporting an area 240 sq.ft., so that the kinetic energy of the roof per foot run of wall is -

$$\frac{60 \times 25 \times 240}{64 \times 72} \quad \text{ft.lb.}$$

The work done in extending the reinforcement is necessarily less than this, since much of the energy will go into elastic vibrations of the roof, etc. Then, if there are A sq.in. of reinforcing bars per foot run of wall, having yield stress 50,000 lb./sq.in. the extension of the reinforcement

* In the actual tests 250 kg. (550 lb.) German S.C. bombs were used.

is necessarily less than δ ft. given by -

$$A\,\delta\,50{,}000 = \frac{60 \times 25 \times 240}{64 \times 72}$$

For 0.06 per cent reinforcement in a 1 ft. thick wall A = 0.06 x 1.44 so -

$$= \frac{60 \times 25 \times 240}{64 \times 72 \times 50{,}000 \times 0.06 \times 1.44} \text{ ft.} = .22 \text{ in. (approx.)}$$

The separation of roof and wall cannot therefore be more than ¼ in. and will probably be much less. In practice it is quite probable that not even a crack would appear there.

This calculation is an example of the use that can be made in design on the one hand of structures which are specifically intended to fail, and, in failing, to give information about the forces causing failure, and on the other hand of the cinematographic technique of velocity measurement, which has been widely used in many connexions and which, as applied to the problem of earthshock movements and velocities, requires only relatively simple equipment. The photographic method also, of course, gives the information necessary to ensure that requirement (c) is met, - that the velocities imparted to personnel in the shelter are not such as to cause injury, regardless of whether the shelter is damaged or not. Walley's paper[8] indicates that the velocities imparted to the shelters are lower than the threshold injurious velocities quoted in paragraph 8.3, but not by much. Clearly it is useless to endeavour to strengthen the shelter further with a view to ensuring that it successfully resists demolition under even more severe conditions, unless at the same time we make it much heavier, so as to prevent the velocity of projection rising above this threshold value. We shall have occasion to consider this point in more detail, when we come to the consideration of "bomb-resisting shelters" (Chapter IX).

One further possibility must be taken into account; the surface shelter must necessarily be capable of supporting a considerable mass of debris on its roof. Moreover, since it is commonly constructed on roads and among buildings, it must be capable of sustaining the impact of heavy masses of masonry, or perhaps large pieces of concrete projected into the roof at moderate velocities. In Chapter IV we have stated that the velocities likely to be achieved by such large missiles as a result of the explosion of a buried bomb are not likely to exceed about 70 ft./sec.

Not much experimental work is available as to the effects of the impact of relatively slow moving missiles on concrete slabs*. All the work quoted in Chapter VII on impact on concrete beams refers to "beams" which were supported at the ends only and failed by simple fracture at the centre. The problem of the slab which under some conditions will fail by "punching" is essentially different. In R.C. 188, however, Gimpel and Marshall reported a valuable series of experiments, although their slabs, being reinforced with expanded metal, were not typical of shelter roof design. The slabs tested were all similar of 3 ft. square and 2½ in. thick, simply supported on a free span of 2 ft. 6 in. with 0.7 per cent reinforcement, and having an ultimate static strength under a central load of about 3 tons. A weight of 7.9 lb. was dropped from various heights on this slab, and it was found the energy required to hole the slab, when the load was distributed over an area 3 in. square was in excess of 200 ft./lb. When a cast iron ball was used as striker so that the area loaded was smaller, the energy required was about half as much. The damage caused was quite local, suggesting that for impacts at moderate velocity the method of support of the slab is not a matter of the first importance.

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* If the bomb explodes immediately below the road surface the velocities will be much higher, but the concrete will be broken up into much smaller pieces.

Applying the dimensional theory outlined in Chapter VI we find that a rigid mass of 63 lb. falling with velocity 40 ft./sec. on to a slab 5 in. thick, similarly reinforced, would just fail to hole it, provided that the area of contact was not less than 6 in. square. In the rough and ready demolitions carried out at the end of the war, a weight of 22 cwt. was dropped 4-5 ft. on to such roofs, and only succeeded in making a hole by repeated impacts on the same point. On this basis it may therefore be expected that the occasions on which shelter roofs of the type shown in Figs. 8.3 and 4, will be holed by debris will be very rare. Experience has confirmed this conclusion. Of shelters built experimentally on concrete roads with reinforced concrete roofs 5-6 in. thick only one was holed by debris in a test under the specified conditions. Cases in which shelter roofs have been holed by debris in actual raids are so rare as to be almost non-existent.

All the causes of injury enumerated in paragraph 8.3 have now been considered, except (d) fragmentation injury and (f) direct blast injury.

In Chapter III we pointed out that walls of the thickness shown in Figs. 8.3 and 8.4 would seldom, if ever, be penetrated by fragments from bombs bursting outside. At the standard 15 ft. distance from the 500 lb. bomb, we showed in Chapter III that the "mass fragmentation" effect would powerfully reinforce the blast effect, but in Chapter VII we argued that these walls would be adequate to resist both acting together. The risk from fragments entering by way of doorways, must of course be combated by providing a suitable "baffle" wall, covering the entrance (or possibly, a suitable fragment-proof door). The complexity of the baffling necessary will vary according to the design of shelter used, but in general it should be such that no fragment can enter the inhabited part of the shelter without at least one ricochet.

A direct measure of the vulnerability of the normal brick surface shelters is not easy since no one standard design was built in large numbers. The shelters actually used were for the most part strengthened versions of the original unreinforced brick shelter, and a number of different systems of strengthening were employed. For example, the exterior of the shelter might be covered by a steel mesh, held in position by an additional $4\frac{1}{2}$ in. brick skin, and by additional concrete on the roof. Alternatively, a similar plan could be adopted in the interior (Fig. 8.7) but in so doing the shelter was rendered considerably safer than the reinforced type designed ab initio as in Figs. 8.3 and 8.4. The walls were 18 in. thick as opposed to $13\frac{1}{2}$ in. thick in the reinforced design, and the roof is also thicker. These increases in weight will improve the performance substantially both against blast and probably also against earthshock.

The evidence of field results is that such a strengthened shelter will not be damaged seriously by blast from a flying bomb at distances greater than about 35 ft. This test is almost certainly appreciably more severe than that imposed by the 250 kg. S.C. bomb (filled TNT) at 15 ft. and accordingly the shelter is somewhat safer than the standard laid down. The reinforced brick shelter Fig. 8.3 is probably only just up to the required standard, although the reinforced concrete is also slightly better. The vulnerable area for the strengthened type could not be estimated with any degree of confidence from the comparatively small amount of field data available, but what there is suggests a value of about 2,700 sq.ft. against the flying bomb. When attacked by a blast weapon the shelter is thus markedly inferior to the Anderson type. When the attack is by penetrating bombs, however, there is little difference between the two.

The public surface shelter is, however, particularly vulnerable to one form of attack which has not materialized in an acute form in this war. There would be no difficulty about designing a bomb of weight about 10-15 lb., charge-weight perhaps 2-3 lb., which would be capable of penetrating the roof of thickness 8 in. or less and exploding inside. The casualties from the internal explosion of such a bomb would be heavy, and even allowing for the fact that owing to fuze defects some bombs would detonate either before penetrating the roof or after passing the floor, the average vulnerable area is likely to be perhaps 100 sq. ft. or more. The vulnerable area per ton aircraft load is then

about 20,000 sq.ft. - more than four times that for the large blast weapon. Such a weapon will be relatively less effective against the smaller shelter types, such as the Anderson, owing to the small area which they present to direct hits.

In addition to the public surface shelters, illustrated in Figs. 8.3 and 8.4 several other types of brick surface shelter were in use. The small domestic type of shelter illustrated in Fig. 8.8 were intended to replace the Anderson shelter when the ground was unsuitable for subsurface construction. Some of the earlier types had arched or corbelled roofs, with a view to economy in steel, but this construction has obvious weaknesses under earthshock, and the usual flat roofs tied by reinforcing to the walls are much to be preferred.

The "communal" type illustrated in Fig. 8.9 consisted in effect of an amalgam of small "domestic" shelters constructed together. The weight of the whole was naturally greater than that of the less heavily partitioned public shelter, and for this reason it was probably slightly safer, particularly against the "small bomb" attack envisaged above. In general, however, all these surface brick shelters, when strengthened up to the 1941 standard could be considered to provide approximately comparable protection.

(iv) The "indoor" shelters

The use of strengthened basements or other strengthened rooms as shelters was widespread early in the war. Provided that the buildings chosen for this purpose were suitable, and that the strengthening was adequate, these shelters afforded a fair measure of security, particularly against blast weapons. In general the requirements were:-

(1) the strutting should be such that the roof was capable of supporting the entire debris load of the building above if it completely collapsed, and moreover should have enough lateral stability to eliminate the possibility of collapse when the roof was loaded unsymmetrically by the collapse of one part only of the building.

(2) The strutting should be so placed that, in the event of the destruction of one or more walls of the shelters by earthshock from a near-miss, it would not be damaged to an extent which would render it incapable of supporting the debris load resulting from the collapse of upper floors. This could be done by placing the main struts at some distance from the exterior walls - never against them. Other minor modifications, such as the bricking up of area lights, etc., were also made, and where the shelter was large in area, it was subdivided by partition walls comparable in strength with surface shelter walls in order to reduce the lethal area of a bomb of medium calibre penetrating into the shelter.

The degree of protection afforded by such a shelter was to a very large extent governed by the nature of the building in which the shelter was placed. In a modern steel-framed building the risk in a basement shelter was very small - probably not more than 1/10th as great as that in the Anderson, if the improved occupancy is allowed for, and by bricking up windows, etc., an equally good shelter could be constructed on the second or third storey of such a building.* Moreover, the weight of debris falling on the roof of the shelter consisting, in a framed building simply of demolished partition walls, etc., can usually be easily carried by the frame without additonal strutting, provided that the roof of the shelter is sufficiently substantial to prevent local collapse. Much the same is true, though the risks were slightly greater, in a reinforced concrete framed building. In any future plan for the protection of the public the utilization of such buildings, which are likely to be more numerous in the future than they have been in the past, may be a prime consideration.

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* For a discussion of steel and reinforced concrete framed buildings cf. Chapter X.

In multi-storey load-bearing buildings of the "monumental" type protection is fairly good particularly against bombs of small or moderate calibre. When the attack is by large bombs serious calamities are likely to occur. The weight of debris falling on a shelter if a large part of the building above is demolished is very great, and the time taken to extract the occupants of the shelter if they have survived, is proportionately long. Although such shelters may be of value in providing "quick" protection for persons working in these buildings they cannot be regarded as satisfactory as a standard type of public shelter.

At the other end of the scale we come to the problem of the provision of a suitable indoor shelter which could be used in the millions of small two-storey houses, terraced, detached or semi-detached, which exist in the country. Few of these houses have cellars or basements and even where these exist, they do not provide any satisfactory protection since the occupants cannot be situated very far from the external walls, and these are as liable to collapse by earthshock as a trench shelter constructed of a non-ductile material. Such a collapse of an external wall is likely to cause injuries at close quarters even if strutting prevents the collapse of the house as a whole.

On the other hand, it was clear by the end of 1940 that an indoor shelter for the small house was urgently desirable. The occupancy statistics (paragraph 8.4) alone argued strongly in its favour, and indeed the idea had been mooted at a much earlier date. The objections which were then foreseen were as follows:-

(a) the shelter could not be such as would decrease substantially the living accommodation in the house, which was, as a rule, already fully utilized. This objection was fatal to most plans for "strutted rooms", etc;

(b) the shelter must be capable of sustaining the debris load resulting from the complete collapse of the house; but access to it, - and escape from it - must be as easy as possible. It was greatly feared that if persons were trapped in such shelters the onset of fire would put an end to the usefulness of the shelter.

It was to meet these objections that the well-known "Morrison" table shelter was introduced; and since this shelter has been, on the whole, the most successful in practice in this war, we shall devote some attention to it.

(v) The Morrison table shelter

Fig. 8.10 shows the design adopted. The details were to some extent determined by the material which happened to be available for the purpose at the time.

The plan area 6 ft. x $4\frac{1}{2}$ ft., while giving adequate room for 2 persons to sleep (4-5 persons were accommodated in a "2-tier" shelter) was not much larger than that of the ordinary table which the shelter was intended to replace. The steel-mesh curtains forming the sides could readily be removed and provided means of access from any direction. It was found that the fears of the pre-war advisers on the subject of fire in debris were not justified. Where a house was so completely demolished that the occupants of the Morrison were left with no route of escape the lack of air supply at all points, except those exposed on the surface of the heap of debris, combined no doubt with the quantity of stone dust suspended in the atmosphere, made it almost impossible for fire to maintain itself in the ruin. Indeed, such demolished houses acted as effective fire-breaks in incendiary raids. True, houses which were only partially demolished or severely damaged were particularly susceptible to fire; but in such houses the occupants of a Morrison usually had at least one route of escape open.

It may be that in the extremely intense fire "tempests" caused by the heavy R.A.F. raids against German cities late in the war, this would no longer have been true. It has been stated that in the heavily built up zone in the centre of a city, when almost every building was on fire, escape by way of the streets became impossible, and casualties due to fire among persons in otherwise undamaged shelters were very high. This, of course, suggests that any type of shelters should be built in an open space and not among a concentration of inflammable buildings. Under the conditions in which the Morrison shelter was most widely used, however, in small houses in areas where the building density was comparatively low, it may be that no fire tempest so severe as to prevent escape from the affected area could have been induced.

The height of the shelter was made low enough to be below window sill level in the average room, and the position in which the shelter was placed was selected to be as far as possible out of range of flying glass. By the methods of Chapter III we can predict that ordinary 9 in. brick walls of a two-storey house were very nearly proof against fragmentation, especially from the higher charge-weight ratio weapons, and that even a $4\frac{1}{2}$ in. brick partition offers a substantial measure of protection.

The main structural requirements were laid down from a detailed consideration of the loads which would be applied to the shelter when the house containing it was demolished.

The shelter had to be capable of sustaining -

(1) A dead load of 320 lb./sq. ft. laid over the whole area of its "roof" or top.

(2) The weight of an area of floor 14 ft. x 6 ft. 6 in. x 20 lb./sq.ft. (the maximum floor area which can strike the shelter when placed in a room in which the supported span is 14 ft.), i.e. the total of the dead load and superimposed load on timber floors of normal domestic occupancy, falling flat on the shelter from a height of 6 ft.

(3) The same area of floor, loaded similarly, hinged about one wall, and falling from the same height to strike the edge of the shelter in an oblique direction.

(4) A horizontal load 160 lb./sq.ft. applied on any side (to resist the horizontal thrust from the debris in a collapsed house).

A full discussion of the design of a shelter to meet these specifications will be found in R.C. 204 "The design and testing of the table (Morrison) indoor shelter". The procedure may be summarized as follows:-

(a) The frame is designed in accordance with the procedure of Chapter VII so that the members are capable of absorbing in plastic bending without excessive displacement the energy imparted to them by the impacts described.

(b) The other parts, e.g. the top plate and the side weld-mesh curtains, and the bottom "mattress" are designed to develop the full strength of the frame.

Actually, the 22 gauge (.03125") plate would be sufficient for the purpose, but in fact a $\frac{1}{8}$ in. steel was used since a supply of the thicker plate was more readily available. It was the original intention to secure the steel laths of the mattress by bending over the bottom angles and securing to the side panel studs. In order to facilitate bundling of the laths for transport this plan was abandoned in favour of attachment by hooks and springs. Experience, however, showed that although the latter plan was reasonably satisfactory, the mattress was inclined to break away from the frame under severe conditions, and it might have been worth while to retain the original design.

The various designs evolved by R. & E. Department, together with a number submitted for consideration by independent designers, were tested "ad hoc" under the conditions described above. Fig. 8.11 shows a test being carried out under conditions (3). Small deformations of the shelter under tests (2) and (3) were considered acceptable, provided they were not so large that the occupants would have been endangered. In the actual tests, the rectangular block of masonry of weight 336 lb. dropped centrally on the shelter was substituted for the floor described in (2) and constituted on the whole a more severe test.

The only risk which remains to be considered is that arising from the shelter and the occupants being thrown about by blast or earthshock. This risk can never be entirely eliminated, particularly in a light shelter; but the Morrison design aimed to reduce it in several ways.

In the first place, the shelter was always provided with a floor of interwoven steel strips, which ensured that if the shelter was lifted, the occupants went with it. Without this floor there would be a serious risk that the occupants would be injured by quite a small displacement of the shelter. Secondly, the mesh sides ensured that there would always be very complete and rapid diffraction of blast inside and outside the shelter, so that no large velocity would be imparted to it by blast. Finally, the horizontal ties at floor level, in addition to contributing greatly to the stiffness and stability of the shelter, went far to ensure that the "legs" of the table would not be driven through the floor on which the shelter stood, with resulting crushing of the occupants between floor and roof.

Turning now to direct field experience of the behaviour of Morrison shelters, we find that, as far as delay-fuzed penetrating weapons are concerned, this is almost entirely lacking, since the shelter did not come into common use until the period (after the middle of 1941) when the enemy confined himself almost entirely to blast weapons. We have however some reliable information, again collected during the flying bomb attack. We can relate the four variables -

(i) casualties to occupants

(ii) damage to shelter

(iii) damage to house in which shelter was placed

(iv) distance from bomb

For this purpose we can define the following categories of shelter damage:-

M1 Shelter destroyed (minimum distance between mattress and top reduced to less than 12 in. as a result of buckling of the top plate, or distortion of the frame)

M2 Heavy damage (minimum clearance between mattress and top more than 12 in. but maximum deflection of top more than 9 in.)

M3 Slight damage (deflections less than 9 in.)

Table 8.3 gives the relation between the type of damage suffered by the shelter and the condition of the house (classified as notes to Table 8.2) in which the shelter was placed.

TABLE 8.3

FATE OF MORRISON SHELTERS IN DAMAGED HOUSES

Category of house damage	Number of shelters damaged to the category					
	Total	M1	M2	M3	Undamaged	Unknown *
A	53	1	1	11	26	14
B	48	0	0	2	46	0
Cb	61	0	0	0	61	0

* If the shelter was not occupied, information about its behaviour was sometimes unobtainable.

It will be seen that out of 39 shelters of known behaviour exposed in houses which were to all intents and purposes totally demolished, only two were seriously damaged, while of 109 shelters in houses seriously damaged, all survived.

This extremely small number of shelters heavily damaged makes it impossible to determine from practical experience what is likely to happen to the occupants of such shelters. Of the five occupants of the two shelters referred to above, only one was injured. Table 8.4 below corresponds in all particulars to Table 8.1 for the Anderson shelter.

TABLE 8.4

DAMAGE AND CASUALTIES FOR MORRISON SHELTERS

Grade of damage	Average circle radius (ft.)	Casualty data								
		No. of shelters studied	Shelters with complete data							
			Number	Total number of casualties			Total No. of occupants	Percentage of casualties		
				K	S/I	L/I		K	K + S/I	K + S/I + L/I
M1	-	1	1	0	0	0	2	-	-	-
M2	-	1	1	0	1	0	3	-	-	-
M3	51	13	12	1	4	4	29	3.4	17.2	31.4

The best that can be done with these rather fragmentary results is to group all the damaged shelters together. We can then find that for persons in Morrison shelters within 51 ft. of the point of burst the proportion of casualties will be as follows:-

No. exposed to risk	No. killed	K + S/I	K + S/I + L/I
34	1	6	10
100%	3%	17.6%	29.4%

The persons further away from the burst are practically safe. The vulnerable area for killed and seriously injured which results, is 1,440 sq. ft. - an even lower figure than that already quoted for the Anderson shelter.

It will be realised, of course, that the more effective a shelter is the less reliable will be the numerical information relating to its performance. As the number of casualties occurring in the shelter decreases, the variations in the number due to chance factors necessarily form a large proportion of the whole. On the other hand, as we noted earlier in this chapter, it would be a cardinal error to attempt to increase the number by investigating, for the purpose of vulnerable area determination, only those incidents in which casualties had occurred. All incidents in which the shelter is "exposed to risk" under the assigned conditions must be investigated, or, at any rate, if a selection is made, the basis of it must be quite arbitrary, and must not be related in any way to the performance of the shelter.

Although, for the reason given above, we have no direct information as to the effect of penetrating bombs against the Morrison shelter we may anticipate that the vulnerable area per ton of bombs will not be greater and may well be less than was the case with the blast weapon. The house damage per ton of bombs, will certainly be less, for example, from 4-250 kg. S.C. or 2-500 kg. S.C. delay-fuzed than from a 1-ton blast bomb, and accordingly we may expect some reduction in the vulnerable area for Morrison shelters.

The small 10-15 lb. bomb, which is a menace to the surface shelter, is also dangerous here. Such a bomb, exploding in the same room as the Morrison would certainly expose the occupants to a severe risk. But the problem of fuzing such a bomb to explode between (say) 15 ft. and 25 ft. below a roof of variable weight, after passing through an upper floor containing a variable amount of furniture of variable resistance, would be very difficult, and it would not be surprising if not more than 1/5 of all bombs striking on the required area exploded at the right level. If, as may well be the case, even these bombs kill or seriously injure only half the shelter occupants the vulnerable area per ton will be found to be no more than that for the large blast weapon.

On the whole, therefore, the Morrison shelter can be regarded as the best (though not incomparably the best) solution to the problem of the shelter of the occupant of the small house. This is especially true when "occupancy" figure is taken in to account. It is probable that the shelter could also be used in the lighter types of three-storey buildings, though the time of rescue of the occupants, in cases where the shelter is buried, is likely to increase sharply with the weight of debris covering it.

(vi) Tunnel shelters

The physical data on which the design of tunnel shelters must be based has already been given in earlier chapters. In Chapter II we described the propagation of blast in tunnels, and in Chapter IV we gave the conditions under which spalling or collapse of the tunnelled rock could be expected. All that is necessary here is to refer to the question of vulnerable area.

We must here differentiate sharply between the effect when the bomb explodes in or very nearly in the tunnel, and the effect when it is sufficiently far away to cause nothing more than spalling of the rock. In the latter case, a local block may occur; but provided that the shelter is furnished with an adequate number of exits so that no large number of people can be trapped by a single fall, casualties will only occur in the limited area in which the fall has taken place. On the other hand, when the bomb penetrates into the tunnel casualties are likely to be numerous, not so much as a result of direct blast effects, as in consequence of the very large "windage" effects which will cause injury both as a result of people being violently displaced themselves, and as a result of the violent displacement of loose material of all kinds. It is therefore essential that in a tunnel shelter which is at a depth at which there is even the barest possibility of penetration, the shelter should be intersected either by numerous blast traps of the kind described in paragraph 2.7 or by extremely strong and heavy blast walls, or both, the number of persons within any one subdivision being strictly limited.

Tunnel shelters have not been used much in the United Kingdom (with the exception of the London tube railways, to which we shall refer again in Chapter XIII), and for an example of a tunnel system in practice, we must return to the German constructed V-weapon sites in the Pas de Calais mentioned in Chapter IV. As we stated, a tunnel system for which the overhead cover above the crown of the tunnel arch was 95 ft., was attacked by 12,000 lb. M.C. bombs fuzed a delay long enough to ensure that the bomb came to rest before exploding. Actual casualty figures for this attack are not available, but if we assume that all persons in the portions of the tunnel completely blocked or very heavily spalled by debris were casualties, we find a vulnerable area of 6,750 sq.ft. per bomb, or 1,260 sq.ft. per ton aircraft load. One of the bombs however "blew through" into the tunnels which consisted of a rectangular system without blast traps or subdivisions of any kind. This bomb would almost certainly have caused many additional blast casualties so that the total vulnerable area per ton may have been in excess of 2,000 sq.ft. per ton - about the same, against this type of bomb, as the small shelters we have described earlier in the chapter. Of course, tunnels at such a depth would be virtually safe against bombs of smaller calibre, such as would commonly be used in attacks on towns. Indeed, in considering the safety of the smaller shelters it is not necessary even to consider if the protection against specially heavy weapons is adequate. The necessity to do so in considering tunnel systems arises from the following considerations:-

(1) A tunnel system constructed to accommodate only a few people is an absurdity. If the overhead cover is to be adequate a large part of the cost will arise from the construction of entrances, shafts, etc., and these, once constructed, could probably without much addition be used to serve a tunnel system of much larger dimensions.

(2) A tunnel system will therefore be constructed only when a large number of people (say 5,000 - 30,000) are to be accommodated.

(3) The plan area of the system so constructed will be considerable: not less than about 1 acre per 2,000 persons, and thus with modern bombing technique it will be possible to be sure of hitting it with a limited number of aircraft, even if the bombs required are so large that each aircraft carries only one bomb.

(4) With a population scattered over the whole town in a large number of diminutive shelters it is useless, from the point of view of causing casualties, to attempt to aim at any selected point; but if a large number of persons are collected in a single shelter, it may very well be considered worth while, as part of a policy directed against public morale, to attack this shelter and to select that type of bomb which is necessary for the purpose.

Thus in designing small shelters, one has only to reckon with those weapons which are likely to be used for attacking any targets which happen to be in the district considered; but when a really large shelter is contemplated every weapon, including those which would be specifically selected to attack the shelter itself, must be taken into account. By collecting large numbers of people together in a tunnel one creates a target where none existed before.

A large tunnel system can therefore only be quite satisfactory if placed at a depth at which there is no possibility of perforation. What depth will in the future be necessary to meet this requirement is, of necessity, a matter for speculation. If we consider only weapons now produced *, it seems that about 160 ft. of chalk or equivalent depths in other rocks should suffice. But if a means is found to delay detonation in a weapon of a high-velocity rocket type, the equations of Chapter I show that this figure may become quite inadequate.

It should be noted that these considerations do not apply to the accommodation of small numbers of persons in existing tunnel systems provided that the cover is reasonably adequate. Where very large underground works exist at depths less than that required for complete safety it may even be possible to utilize them to accommodate a reasonable number of people provided that on the one hand the population density in plan is not large enough to present an attractive target to the enemy, and on the other hand that the tunnels are provided with such substantial sub-divisions that the effects of an internal explosion are confined within a reasonably small area.

8.6 The "calamity" risk

It will be realized that the remarks above in reference to tunnel systems applies, mutatis mutandis, to all large shelters. Not only is a large shelter more likely to be deliberately attacked, but, in addition, when successfully attacked, the large number of casualties resulting simultaneously constitutes a much more serious problem than an equal number distributed in a number of small incidents over a period of time. Rescue and medical services, for example, are very much better able to cope with a continuous trickle of casualties than with an equal number arriving together; and it is widely believed, though as far as the writer is aware, it cannot be proved, that such calamitous incidents have an adverse effect on morale.

For these reasons the British policy has been throughout this war to eliminate as far as possible the "calamity" risk by never concentrating a large number of people in a single shelter except when an extremely high degree of security could be offered. A large shelter, to be as safe as a small one, has to be a great deal safer.

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* Written in June, 1945.

APPENDIX

THE DISTRIBUTION OF EXPENDITURE[9]

In the preceding pages, we have reviewed briefly the essential structural requirements in a shelter. We have shown that in many cases, advantage can be taken of existing buildings to provide protection better than that which could be provided ab initio for the same expenditure. Evidently then, the form which shelter provision should take in a given locality should be governed in many cases by the local conditions, by the nature of the existing buildings, by the local availability of materials, etc. Nevertheless, it is useful to consider briefly the quite general problem of the way in which a fixed expenditure, available for protection of a given area - say a large industrial town - should be distributed.

Suppose that the area under consideration can be divided into a number of localities of area S_1 S_2 S_3 ..... sq. miles, in which the expected density of attack is N_1 N_2 N_3 ..... ton/sq. mile, and suppose that the protection provided in these areas is such that the mean vulnerable area per ton for the inhabitants, (when allowance has been made for occupancy) is A_1 A_2 A_3. The chance that any one person will become a casualty is then $N_1 A_1$, $N_2 A_2$, $N_3 A_3$ respectively, provided that these fractions are small compared with unity and, if the population density is D_1 D_2 D_3, etc., the total number of casualties is -

$$N_1A_1D_1S_1 + N_2A_2D_2S_2 + N_3A_3D_3S_3 \quad \text{............} \quad (8.6)$$

Now let us suppose that the relation between vulnerable area and cost per head of population is -

$$C = f(A)^{*}$$

and that the values of C corresponding to A_1, A_2, A_3, are C_1, C_2, C_3.

Then we have the total expenditure C given by

$$D_1S_1C_1 + D_2S_2C_2 + D_3S_3C_3 + \cdot \cdot \cdot = C \quad \text{.......} \quad (8.7)$$

Various "policies" are of course possible. For example, we might decide that a constant expenditure per head of the population should be made throughout ($A_1 = A_2 = A_3$, $C_1 = C_2 = C_3$). In equity, it might be argued that everyone ought to run as nearly as possible an equal risk ($N_1A_1 = N_2A_2 = N_3A_3$) or taking a somewhat more hard-headed view, that the objective is to minimize the total casualties given by (8.6) above.

If we accept the "equal risk" theory, we have of course -

$$A_1 = \frac{k}{N_1} \quad A_2 = \frac{k}{N_2} \quad \text{etc.} \quad \text{............} (8.8)$$

and k is determined by substituting C_1, C_2, C_3 in (8.6)

If we accept the "minimum total casualties" therefore, we can proceed as follows:-

Suppose that we make a small increase in the expenditure in zone (1) ΔC_1, at the expense of zone (2) then we have

$$D_1S_1\,\Delta C_1 + D_2S_2\,\Delta C_2 = 0 \quad \text{...........} \quad (8.9)$$

But $$\Delta C_1 = \left(\frac{\delta f}{\delta A}\right)_1 (\delta A)_1 + \Delta C_2 = \left(\frac{\delta f}{\delta A}\right)_2 (\delta A)_2 \quad \text{...........} \quad (8.10)$$

So thus $$D_1S_1\left(\frac{\delta f}{\delta A}\right)_1 (\delta A)_1 + D_2S_2\left(\frac{\delta f}{\delta A}\right)_2 (\delta A)_2 = 0 \quad \text{...........} \quad (8.11)$$

---

* It is here that the argument lacks generality. This function is not single valued but depends on the local circumstances.

Since the total number of casualties (8.6) is an absolute minimum, the effect of this small change in expenditure must be zero and

$$N_1D_1S_1\ (\delta A)_1 + N_2D_2S_2\ (\delta A)_2 = 0 \qquad \ldots\ldots\ldots (8.12)$$

Eliminating between (8.11) and (8.12) we find

$$\frac{1}{N_1}\left(\frac{\delta f}{\delta A}\right)_1 = \frac{1}{N_2}\left(\frac{\delta c}{\delta A}\right)_2 \qquad \ldots\ldots\ldots (8.13)$$

and by making similar small changes in C_3, etc., we find that this equation can be extended to all indices and since on our hypothesis C is a function of A only, we can write -

$$N_1\left(\frac{\delta A}{\delta C}\right)_1 = N_2\left(\frac{\delta A}{\delta C}\right)_2 = N_3\left(\frac{\delta A}{\delta C}\right)_3 \text{ etc. } \ldots\ldots (8.14)$$

We note that if the equation relating cost and vulnerable area is of the form

$$A = A_0C^{-KC} \qquad \ldots\ldots\ldots (8.15)$$

the equation (8.7) obtained on the "equal risk" hypothesis is identical with equation (8.14) obtained on the "minimum casualties" hypothesis. In certain areas which do not lend themselves readily to any one type of protection, the equation may well be approximately true, but very often it will be found impossible to improve protection by increased expenditure, at the rate required by (8.15), so that if it is required to retain the "minimum casualties" hypothesis, there is nothing for it but to admit that the inhabitants of the most heavily attacked area must accept a greater risk*.

The defence of an essential command post, or military fortification, offers a parallel problem. Here the alternatives are to have one immensely strong erection, having an exceedingly small vulnerable area, or to have several duplicate posts of less strength. Suppose the vulnerable area of the single unit is A_1, the density of attack being D_1. Then the probability of destruction is $1 - e^{-A_1D_1}$. In the alternative case, N similar units each have vulnerable area A_N and the probability that they will all be knocked out is:- $(1 - e^{-A_ND_1})^N$.

The cost of the single unit is C_1, and for equal expenditure, the multiple units of course cost $C_N = \frac{C_1}{N}$. Thus duplication is undesirable provided that -

$$1-e^{-A_1D_1} < \left\{1-e^{-A_ND_1}\right\}^{C_1/C_2} \qquad \ldots\ldots\ldots (8.16)$$

Now if A_1D_1 is small, equation (8.16) can be written in the form -

$$A_1D_1 < (A_ND_1)^{C_1/C_2}$$

or, for the case when duplication only is contemplated

$$A_1D_1 < \sqrt{A_2D_1}$$

Thus, for example when $A_1D_1 = \frac{1}{100}$, duplication is worth while unless the single structure is ten times safer than each of the duplicates.

If A_1D_1 is large (>1) we proceed as follows:-

Duplication is undesirable if -

$$1 - e^{-A_1D_1} < 1 - 2e^{-A_2D_1} + e^{-2A_2D_1}$$

$$e^{-A_1D_1} > 2e^{-A_2D_1} - e^{-2A_2D_1}$$

* This can be very easily demonstrated if we take occupancy into account. Suppose that a Morrison shelter has a vulnerable area $\frac{1}{8}$ that of an unprotected house, and that its "occupancy" is 80 per cent. Then in an area attacked three times as heavily, a perfect shelter (one of vulnerable area zero) would have to have an occupancy of 95 per cent - an almost impossibly high figure - to give an equal risk).

Now since A_2D_1 is still larger, the last term can be neglected, and we have duplication undesirable if

$$e^{A_1D_1} \qquad \tfrac{1}{2}e^{A_2D_1}$$

$$A_1D_1 \qquad A_2D_1 + \log \tfrac{1}{2}$$

Thus the larger A_1D_1 becomes the smaller must be the ratio A_2/A_1 in order that duplication may be worth while. If the risk to the single installation is high ($A_1D_1 \quad 1$) the duplicates have to be almost as safe as the original in order to offer any advantage. Duplication of defences is an excellent means of eliminating the risk of an unlikely calamity, but it is almost useless for buttressing a forlorn hope.

Of course, in the example we have quoted there are many other factors to be taken into account; for example, the persons manning the fortification may have their own opinion as to how strong it should be; but there are many installations, such as communication cables, power supply systems, etc. in which the whole basis of the problem is summed up in the few lines above.

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5 See also R. & E. Department "A study of the safety/cost relation in different types of dwelling" R.E.N.177, October, 1942.

6 This and the following tables are taken from R. & E. Department "The relative effectiveness of various types of shelters against flying bomb attacks" R.E.N.464, January, 1945.

7 Zuckerman, S. "The field survey of air raid casualties" R. & E. Department R.C.270, November, 1941.

8 See for example:- Walley, F. "Movement of shelters due to earthshock" R. & E. Department R.C.287, January, 1942. In this paper it is shown that the maximum velocity imparted to the standard surface shelter as a whole, from a 250 kg. bomb at 15 ft. horizontally from the shelter wall, and 12 ft. 6 in. deep is about 10 ft.-sec. somewhat less than that imparted to the ground at the point in the absence of any surface load.

9 The argument here given will be found in more detail in R. & E. Department "Protective measures in new dwellings: an approach to the policy of expenditure" R.C.330A, June, 1942.

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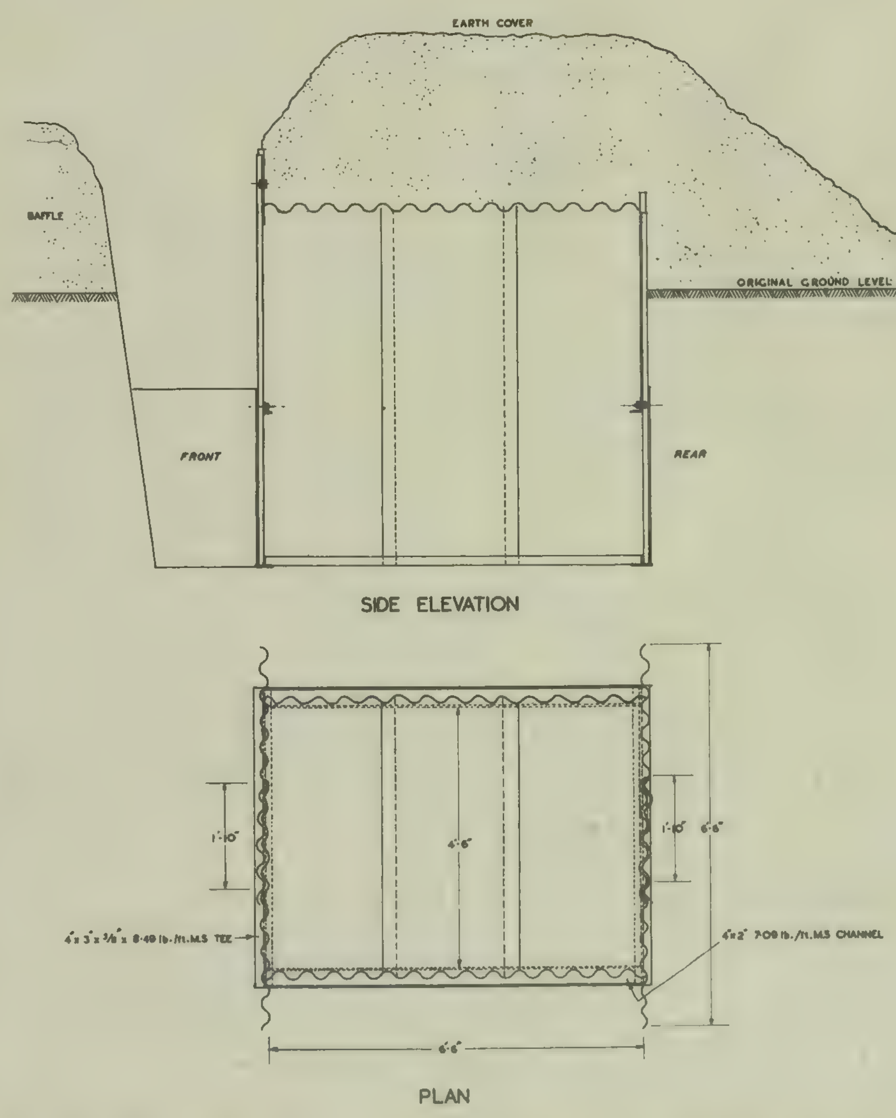


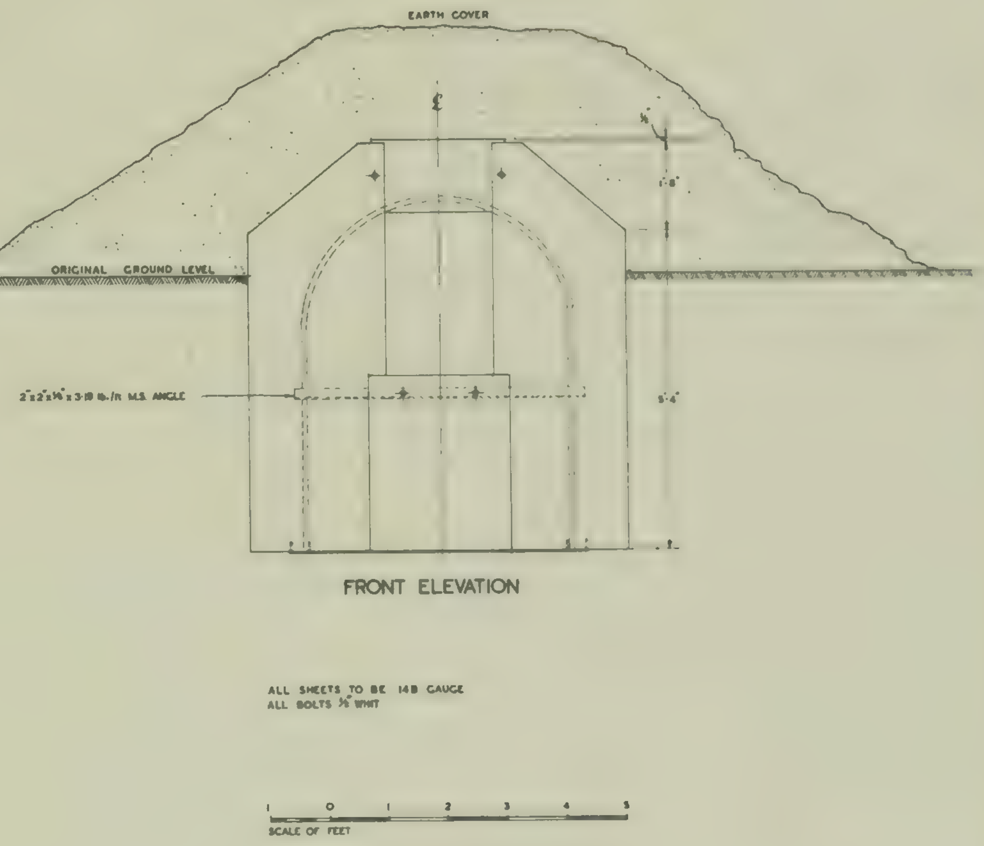
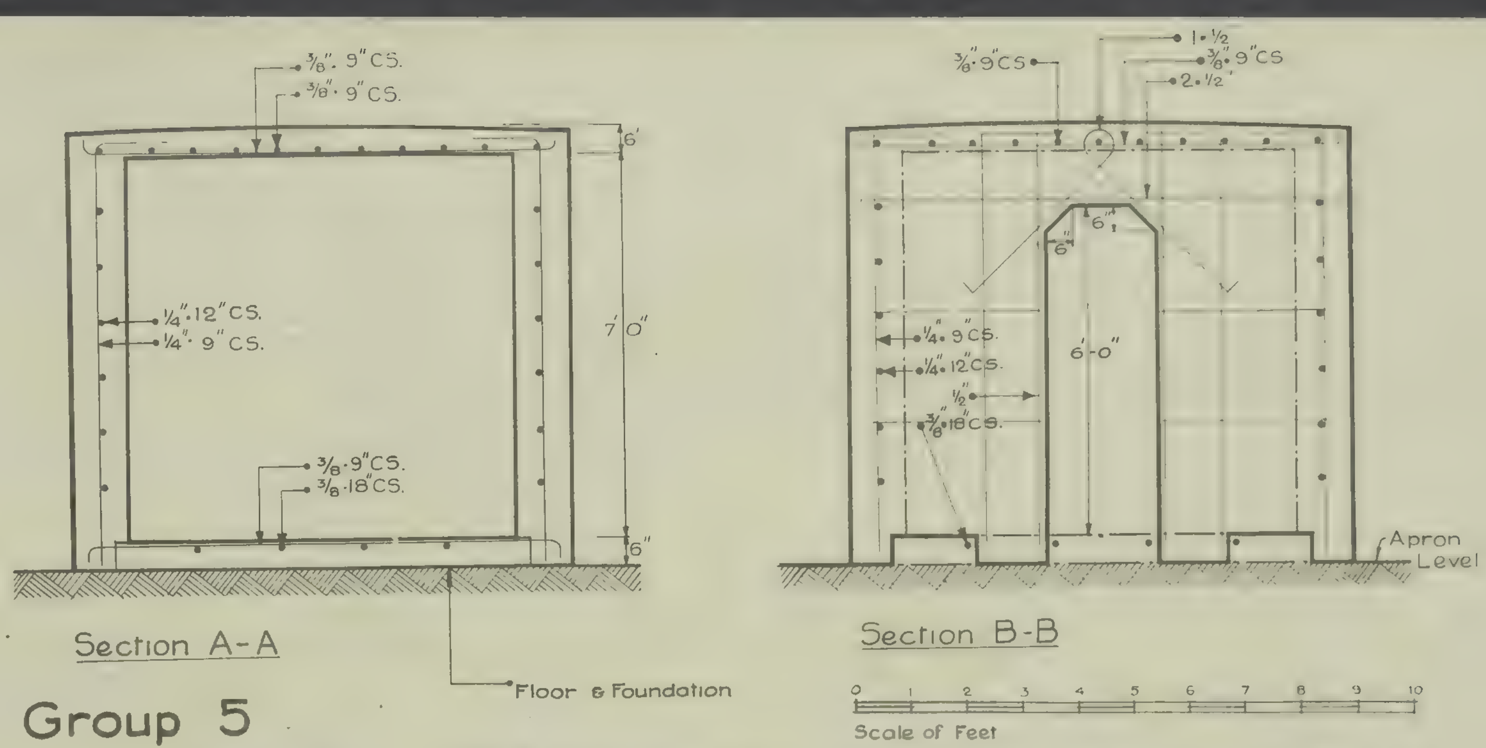
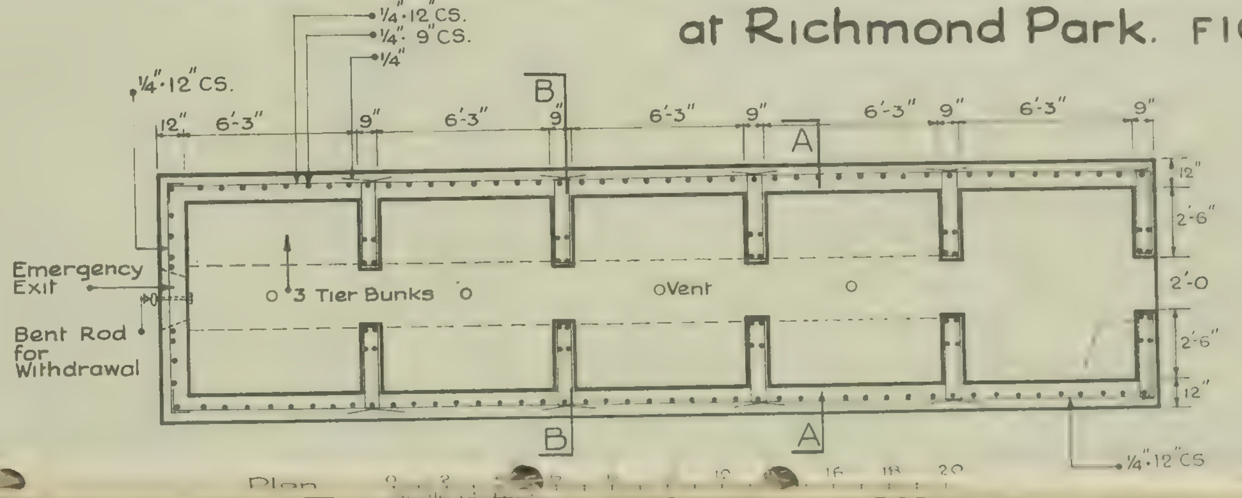


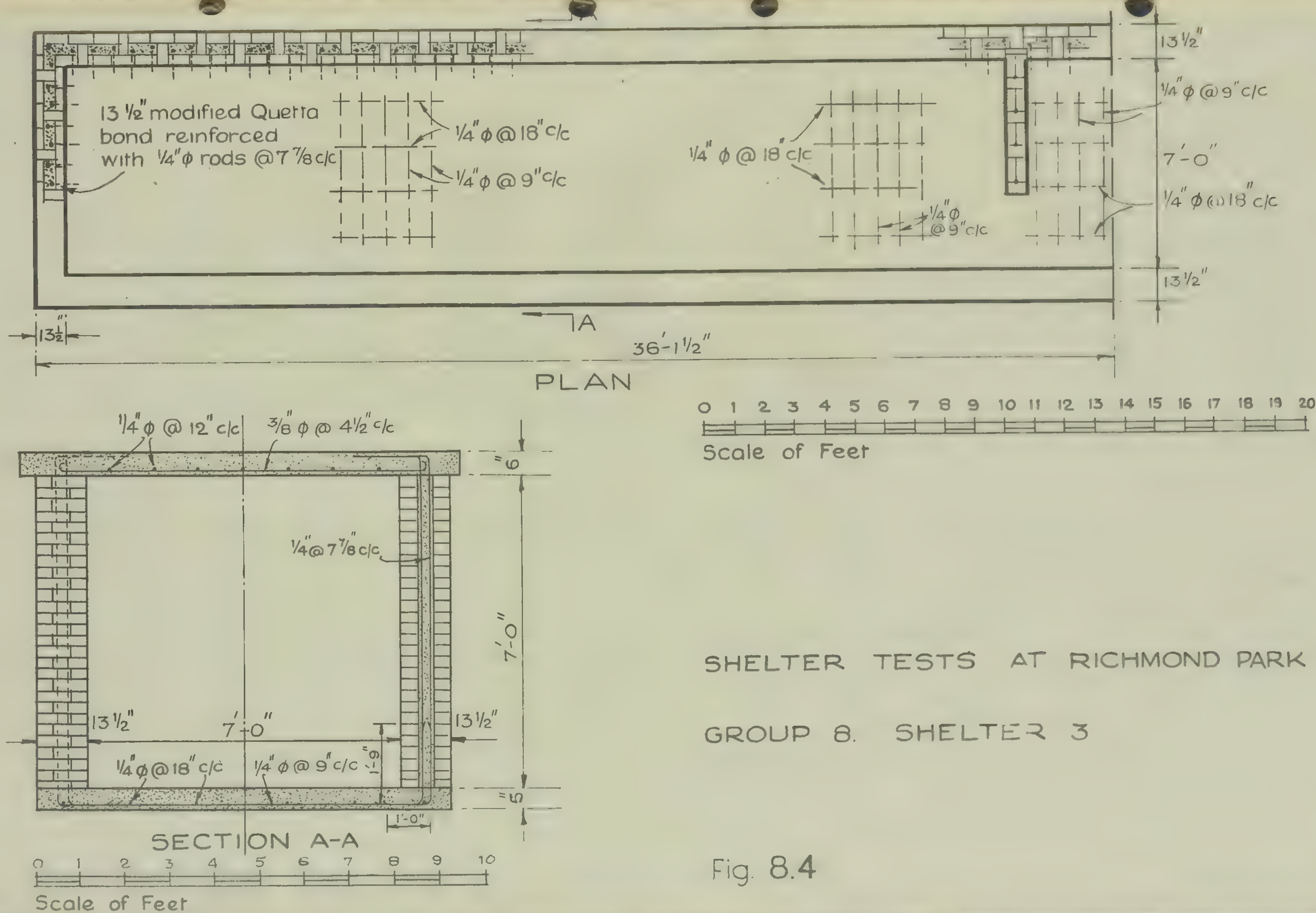
FIG. 8·1 ANDERSON SHELTER



Group 5

Shelter No. 2-Reinforced Concrete Shelter Test at Richmond Park. FIG. 8.3.



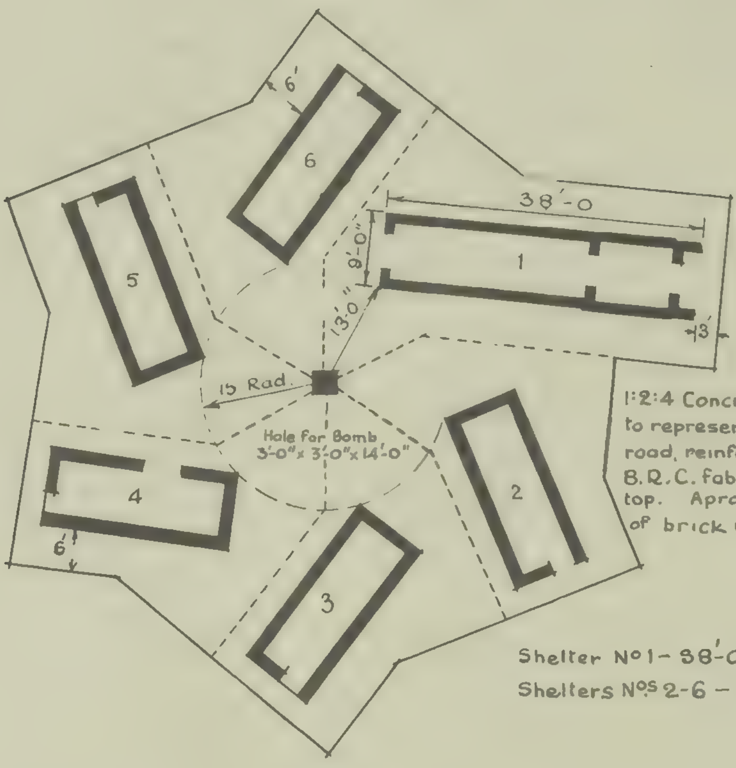


SHELTER TESTS AT RICHMOND PARK

GROUP 8. SHELTER 3

Fig. 8.4

Shelter Nº 1 - Reinforced concrete.
Shelter Nº 2 - Reinforced brick skin.
Shelter Nº 3 - Normal type.
Shelter Nº 4 - R.C. inner skin with base plates.
Shelter Nº 5 - do: with R.C footings under wall.
Shelter Nº 6 - R.C. inner skin with floor.



1:2:4 Concrete apron 4" thick to represent building estate road, reinforced with Nº 9 B.R.C. fabric placed 2" from top. Apron to be laid on 6" of brick rubble

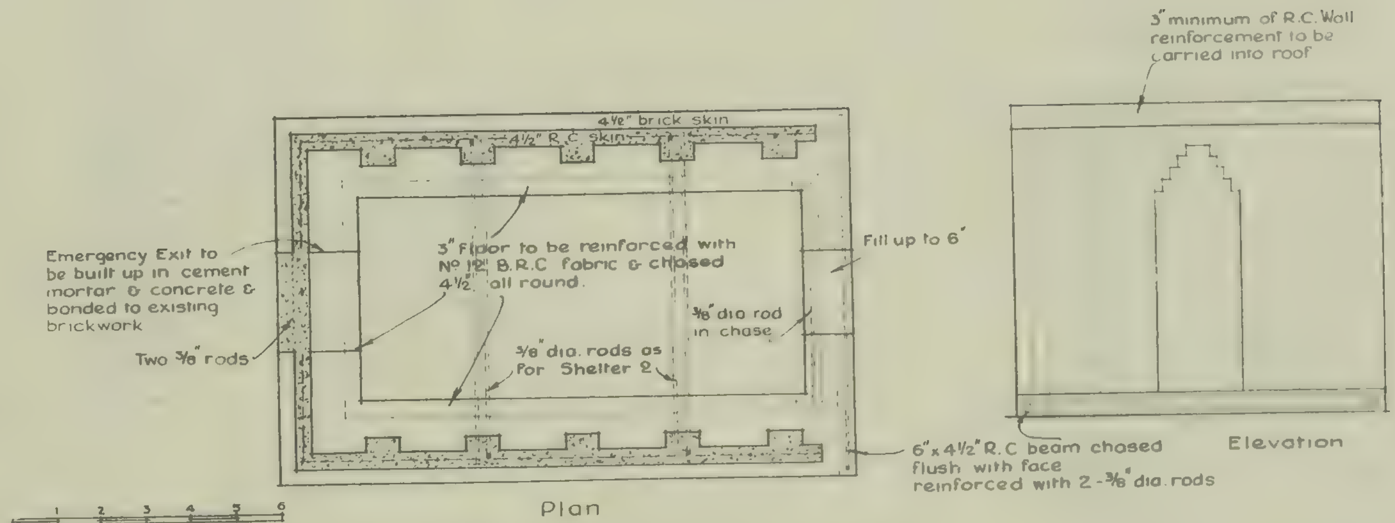
Shelter Nº 1 - 38'-0" x 9'-0"
Shelters Nºs 2-6 - 22'-3" x 9'-3"

GROUP 1.
PROPOSED SHELTER TEST
TO BE HELD AT RICHMOND PARK

FIG. 8.5.

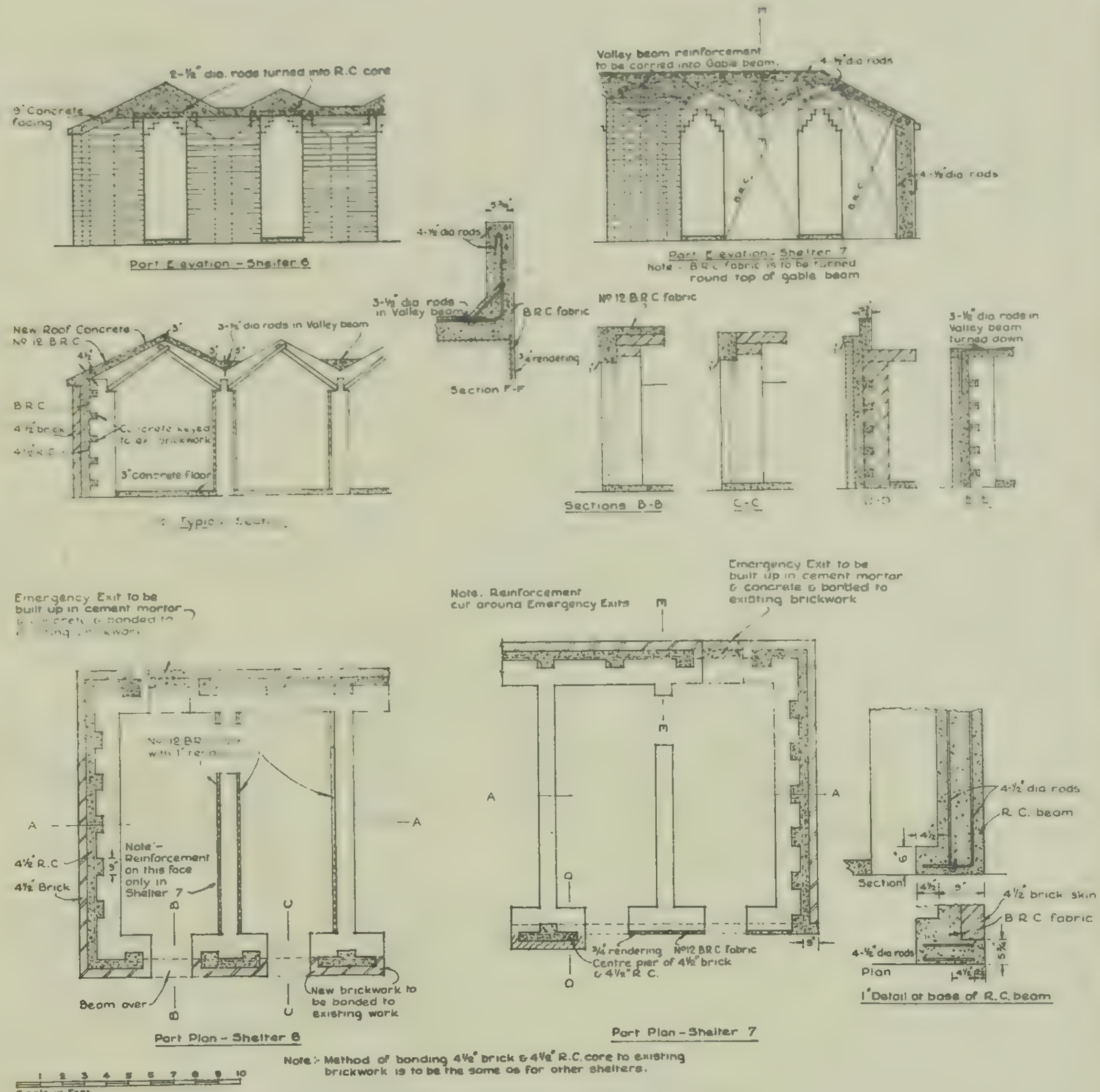
Fig.8.6 Effect of ground-shock from a buried bomb on a group of unreinforced brick surface shelters. The roof of the shelter on the left is seen separated from the walls while that next to it has its back broken by the movement. (Paragraph 8 & 31)

Fig.8.7 Effect of ground-shock on a group of reinforced brick surface shelters and one reinforced concrete shelter (on extreme left). Note how shelters are thrown into the air without fracture. (Paragraph 8)



Group 4. Reinforcement of Shelter Nº 1

FIG. 8-8



Group 4. Communal Shelters — Details of Reinforcement.

FIG. 8.9

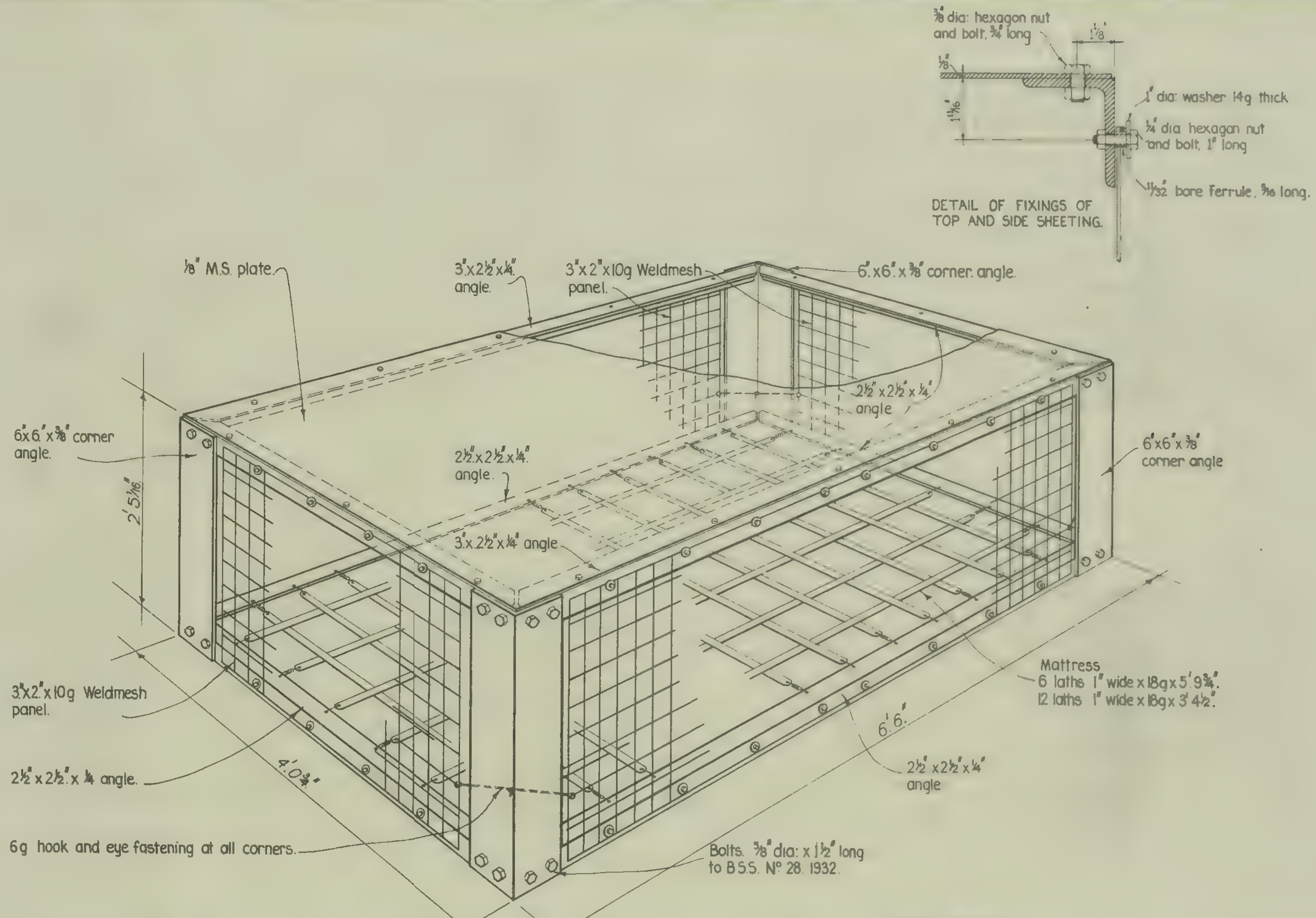


FIG. 8·10.

FINAL DESIGN OF INDOOR TABLE SHELTER.

Photo 1.

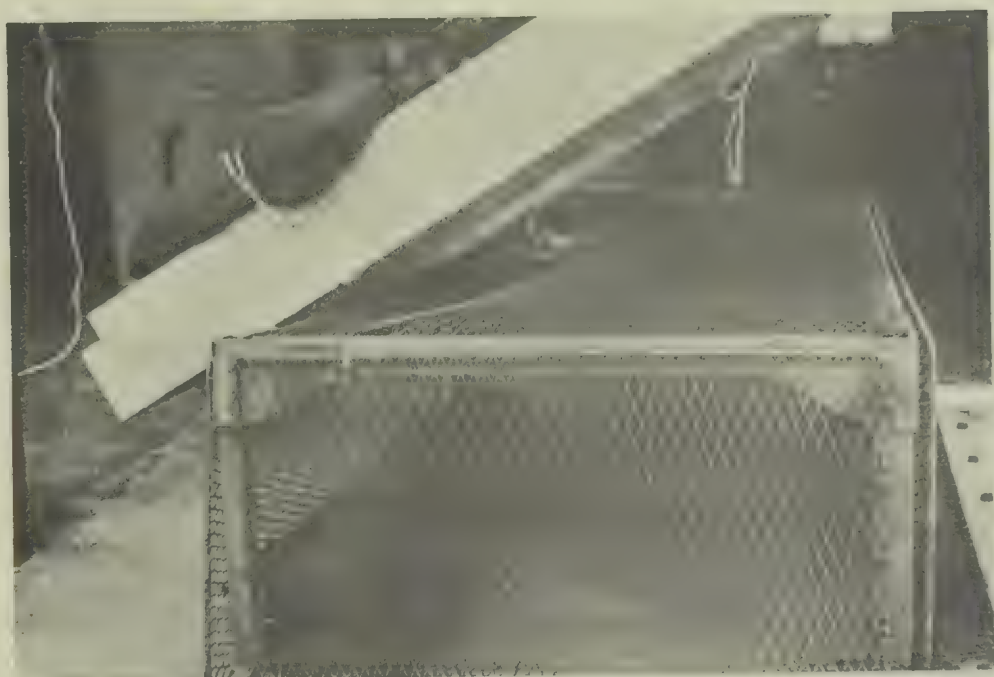


Photo 3.

Fig. 8.11 Falling floor impact test on indoor shelter.

CHAPTER IX

"BOMB-PROOF" SHELTERS AND FORTIFICATIONS

9.1 The meaning of "bomb-proof" and "bomb-resisting"

Ten years ago the word "bomb-proof" was self-explanatory. A building was "bomb-proof" if it could not be seriously damaged by any bomb capable of being carried in an existing aircraft. Even then, the requirements for a "bomb-proof" shelter were onerous, and necessitated extremely heavy construction, but they were within the bounds of possibility, provided that only a moderate amount of "bomb-proof" accommodation was required within the building.

At the beginning of the war, it was realized however, that a shelter, designed to be proof against the largest bombs then in service or under development, would require an expenditure of labour and material so large that it could only be justified in very exceptional circumstances. A few such "1939 bomb-proof" shelters or "fortresses" were constructed, mostly for housing an operational command headquarters of the fighting services, and this standard of construction became known as "fortress protection". Judged by 1945 standards, it is not completely bomb-proof, and indeed it is very doubtful if there exist anywhere, constructions capable of resisting the largest penetrating bombs now in use.*

Between the small shelters described in the last chapter, and the "fortresses" there was a very wide gap, both in safety and expenditure, and to bridge it a third standard of protection was introduced - the so-called "bomb-resisting" shelter designed to be safe against bombs up to weight 500 lb. This standard necessitated a roof about 6 ft. thick in reinforced concrete (as opposed to the 10-12 ft. roof of the fortress) the other dimensions - walls, and floors, - being in proportion. Although not many shelters of the bomb-resisting type were built in Great Britain, we have considerable direct evidence of its behaviour, a very similar standard having been widely used by our opponents. Many fortifications of the "Atlantic wall" were constructed approximately to this standard; and also a number of the formidable "Bunker" shelters, erected in the cities of western Germany, when it became clear that an effective reply was being made to the earlier German attacks on British industry. Naturally, a good deal of experimental work was done in this country, in order to develop means of attacking the Atlantic wall and the Bunker shelters were often hit during our large-scale industrial raids.

Finally, a reference must be made to the last attempt made by the Germans to attain truly "bomb-proof" construction - in the submarine pens on the Atlantic coast, and on the "large sites", the huge concrete erections in the Pas de Calais which were intended to provide safe bases from which various "V" weapons could be aimed at London. When planned, these structures were undoubtedly believed to be practically bomb-proof (their roof thickness was over 16 ft.). The air campaign by which they were defeated forms not the least interesting narrative of the war.

For the present purpose, we need make no distinction between shelters and fortifications. The latter are simply shelters with a special purpose which may modify their form, for example, by necessitating an embrasure, which somewhat decreases the protection afforded, but in general the principles of design will be the same regardless of the purpose for which the shelter is intended.

Furthermore, whereas in dealing with small shelters, we had at our disposal a number of totally different types of protection involving different materials used in different ways, in the present chapter we shall deal almost exclusively with one material - reinforced concrete - and the general form of the protection offered will not vary much. We shall find as before that both surface and sub-surface shelters are possible in various conditions and that a wide range of geometrical shapes can be considered. In all types, however, we must provide a roof capable of resisting perforation, walls capable of resisting near-misses, whether in air or in earth, and a floor to resist the earth-shock from a more or less remote burst. Very occasionally, we may consider the use of armour plate for a special purpose, but the introduction of an entirely new type of "bomb-resisting" shelter on an entirely new principle (as the Morrison was introduced in the middle of the war) seems most unlikely.

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* We exclude a number of very deep tunnels, mines, etc., which are not constructions in this sense.

9.2 Methods of attack - direct hit and near-miss

Obviously any structure is liable to receive a direct hit or a near-miss. The larger the plan area of this target the more important relatively will be the former. In the very small shelters described in the preceding chapter we were able to give a very fair measure of protection without attempting to provide any defence whatever against a direct hit from any but the very smallest bombs. Our whole aim was to reduce the area in which a near-miss could inflict serious damage. At the other extreme, in the expanses of the submarine pens, often many acres in extent, the risk of serious damage by a near-miss was practically trivial, and the whole purpose of the designer was first to provide a roof which would prevent perforations, and secondly, if this was impossible, to subdivide the interior in such a way that the area of damage caused by a bomb exploding inside was as far as possible restricted.

The bombs required for an attack on a heavy concrete structure differ according to whether the primary aim is to effect damage by direct hit or by near-miss. The near-miss attack requires an "M.C." bomb of charge-weight ratio about 50 per cent, which will probably, though not certainly, break up or detonate prematurely in the event of a direct hit. Two or three special types of bombs can be used for a "direct hit" attack; in general the charge-weight ratio of each is below 50 per cent and so, if a near-miss is scored the earth-shock or blast damage will be less than would be the case with the M.C. type. Accordingly the attacker must make up his mind beforehand whether his primary aim is to score direct hits or near-misses, and must select his bombs appropriately, knowing that if by chance his bombs score in the other category he will achieve less than maximum damage.

In practice, his choice is often influenced by the fact that his target consists not only of a number of heavy concrete structures but also of a complex system associated with them. In fortifications, for example, there are likely to be trench systems for local defence, cables for power and communications, roads or railways for supply purposes and so on. All these targets are best attacked by M.C. bombs, and for this reason the attacker will endeavour to retain these bombs - the near-miss type - wherever possible. A useful though inexact rule is that where the minimum weight of the bomb necessary to perforate the roof exceeds that of the bomb whose crater diameter (delay-fuzed) equals the width of the structure (the minimum plan dimension) then the attack should be by near-miss.

It follows that there is a certain limit beyond which it is useless to strengthen a small surface or sub-surface shelter.* Suppose its diameter is 30 ft. and that its floor is not more than 20 ft. below the surface, then a near-miss by an M.C. bomb of weight 4,000 lb. making a crater 60 ft. across will blow it out of the ground and will almost certainly put its occupants out of action. A shelter of this size cannot therefore be protected against 4,000 lb. bombs, and thus to provide it with a roof more than about 12 ft. thick, with a view to resisting bombs of this size or larger is practically useless. It will only prove useful if by some mischance the enemy elects to attack by direct hit. Of course, a shelter of the dimensions given is a most uneconomical proposition. A roof of this thickness can seldom be justified unless it provides a considerable protected space.

We have now to consider in detail the five main causes of damage to heavy concrete installations:-

(i) Direct hit, with instantaneous fuze: explosion in contact with roof.

(ii) Direct hit, with delay fuze: penetration or perforation followed by explosion.

(iii) Near miss, with instantaneous fuze: explosion near or in contact with walls above ground level.

(iv) Near miss, with delay fuze: explosion near or in contact with walls below ground level.

(v) Near miss, with delay fuze: explosion below shelter near or in contact with floor.

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* Assumed to be built on penetrable soil. On hard rock very great strength is possible in a small shelter.

We have already in Chapter I dealt at some length with the question of penetration, and in Chapter IV we have given some consideration to the effect of near explosions in earth. Some account must now be given of the effect of contact and very near explosions in air, and we must give further attention to contact explosions below the surface under conditions of confinement.

9.3 Contact explosions in air

Earlier in this book it has usually been possible to describe the effects observed simply in terms of the weight of the charge, and its position relative to the target. We can add definition to this latter phrase by referring always to the position of the centre of mass of the explosive. When we come to the study of contact explosions, however, it is no longer possible to leave out of account the effect of the shape of the charge, and as every student of demolition technique knows, the "closeness of contact", or absence of the most tenuous layer of air between charge and target has an important effect in increasing damage*.

For our present purpose, however, we are assuming that the attack is by projectiles, whether air-borne or not, which are of a quite unsuitable shape for establishing geometrically close contact with the plane surfaces of a fortification. We can, therefore, assume that the attacker does not in general enjoy the benefits of a real contact shot,** and in what follows we assume that contact is never closer than might be obtained by placing the charge against the surface without any special precautions.

In practice we are interested chiefly in a cylindrical charge of length about three to four times its diameter, either lying on the target with its axis parallel to the surface (the "sideways-on") or standing normal to it, with one end in contact (the "nose-on" position). For the most part we shall be interested in cased-charges, of medium or low charge-weight ratio, though we have little or no evidence that case weight is a matter of importance, when contact charges are under consideration.

The experimental evidence on this subject is not as complete as one could wish. A few generalizations, derived for the most part from small-scale experiments, may first be quoted.

(i) Light reinforcement does not have much influence in the size of the surface crater formed by a contact charge, but reinforcement near the rear face, particularly if in the form of a close mesh, may have an important effect in reducing scabbing.[1]

(ii) The crater volume varies approximately inversely as the square root of the concrete crushing strength. The tendency is for the depth of the crater to vary more than the diameter as the crushing strength varies[2]. There does not seem to be any very substantial correlation between the total thickness scabbed and the crushing strength[3] provided that the latter falls within reasonable limits (say 2,000-7,000 lb./sq.in.)

(iii) The crater made in a slab only just thick enough to resist the explosion is substantially smaller than that in a thicker slab.[3] This somewhat curious result might perhaps be used as a starting point in the further investigation of the mechanism of crater formation.

In Table 9.1 we give the results of a few full-scale and small-scale tests. These results are not complete; they do not, for example, enable us to say what is the minimum scabbing plate or rear mesh of reinforcing which will produce the effects described. However, they do suggest the following conclusion:- A mesh of mild steel reinforcement of the order of 0.5-1 per cent by volume, concentrated near the inner face will retain the shattered concrete in the scab from a sideways-on

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* Except in the one important case - that of the "shaped" Monroe charge - which, as we describe below, works best with a specified "offset" or space between charge and target.

** Some small bombs have been constructed with plastic explosives which are supposed to flatten themselves into close contact on striking the target. Some infantry anti-tank weapons are of this type, but it has not been used on any appreciable scale for aircraft bombs or shells.

contact explosion and will not bulge outwards by more than about 1/7 span (an acceptable maximum) provided that the thickness of concrete (inches) exceeds nine times the cube root of the charge-weight (lb.) (TNT or amatol). Similar tests have shown that under the same conditions for an explosion in the "nose-on" position, the necessary thickness of concrete (in.) will be about five times the cube root of the charge weight (lb.) of T.N.T. and that in the absence of a rear scabbing or "soffit" plate, the concrete cover on the inside reinforcing will be displaced more or less violently unless the thickness is about double that specified. The use of the steel soffit plate on the interior surface is desirable in almost all cases. Very often this plate can be made to take the place of shuttering during construction, and thus serve a double purpose.

Other experiments have thrown light on the effect of detonating a charge "nose-on" in a crater of the dimensions formed by the impact of a bomb of the corresponding size. Provided that the target slab is thick enough to resist the impact penetration and scabbing at (say) 900 ft./sec. the subsequent explosion is not likely to add greatly to the damage, particularly if a soffit plate is provided. The crater diameter is enlarged by the detonation, but its depth is often practically unchanged. It is a curious point that the thickness of concrete required to resist impact scabbing by M.C. bombs dropped from high levels, is very nearly the same as that required to resist the side-on contact explosion of the same bomb, which might occur in a low-level attack with an anti-ricochet device. The following table of proof thickness calculated from the equations of Chapter I and from the rules given above will make this clear:-

TABLE 9.2

PROOF THICKNESS FOR BOMB-PROOF ROOFS

Bomb (German medium-case type)	Penetration at 1000 ft./sec. (in.) (i)	Thickness perforated at 1000 ft./sec. (in.) (ii)	"Proof" thickness to resist scabbing (iii)	Proof thickness to resist perforation by sideways-on contact shot (in.) * (iv)
50 kg. S.C.	15	26	35	34
250 " "	27	47	64	59
500 " "	36	61	82	71
1000 " "	41	75	111	93

We note that the difference between column (i) and column (iii) always exceeds 5/9 x column (iv), the thickness perforated by a nose-on shot.

The use of a high charge-weight ratio bomb would increase the thickness necessary to resist the sideways-on explosion without increasing the load on the aircraft, but in general this form of attack is not greatly to be feared. At best it can do only local damage in the interior, less serious than that which will be caused by an internal explosion after perforation of even a small bomb.

The experimental evidence on the question of the effect of decreasing the percentage of reinforcing is quite inadequate. The argument of Chapter VII suggests that a reduction from m per cent to n per cent in the percentage of steel, (retaining the same distribution) will reduce the energy-mass product in ratio not exceeding n/m. If, as is probably the case for the very large thickness-span ratios which we are dealing with here, a large proportion of the strength comes not from tension in the reinforcing but from arch action in the concrete, then reduction in the percentage reinforcing will have an even smaller influence on the resistance. An increase in thickness from t to t', however,

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* The presence of rear reinforcing and scabbing plate is assumed.

produces an increase in the energy-mass products of at least $(\frac{t'}{t})^2$ or $(\frac{t'}{t})^3$ if arch action is important. Thus, as far as resistance to "bulging" and "general" deformation is concerned, a reduction from m per cent steel to n per cent steel is likely to be offset by an increase in thickness from t to t' given by:-

$$\frac{t'}{t} = \sqrt[p]{\frac{m}{n}}$$

when the parameter p is unlikely to be less than about 3.

The factor of real importance however, is not so much bulging as local damage, cratering and scabbing. Reinforcement has little if any effect in reducing cratering, but it has an important influence in retaining the scab. What is essential for this purpose is not that the reinforcing bars should be heavy, - the bars in the rear face of a slab are seldom cut, even when the slab is completely holed by an explosion,* - but that they should form a very close mesh, well anchored by through bars into the interior and thus capable of retaining the concrete even when considerable shattering has taken place. What is wanted therefore is not a high percentage of all-through reinforcement (a close mesh through the whole of the very thick walls and roofs which we are here considering will only increase the difficulty of pouring a high strength concrete) but a very close mesh of small bars near the inner surface, well tied to a comparatively wide mesh in the solid, which simply serves to prevent the general shattering to be expected in unreinforced concrete. The system of reinforcing shown in Fig. 9.6b, although it totals no more than 0.34 per cent by volume on the average would probably be capable of standing up quite as well as those whose tests are referred to in Table 9.1. Of course, it is assumed throughout that the reinforcing is such that the roof has an adequate factor of safety under ordinary static gravity forces. In most cases, this requirement will be met by the type of reinforcing which we have specified for providing resistance to explosion, particularly as the supported span of the roof is usually only a few times its thickness. Where a large open space is required beneath a heavy roof, it will sometimes be found that extra tension reinforcing must be added in order to provide an adequate factor of safety against ordinary bending forces.

It is not easy to specify exactly what constitutes this "adequate factor of safety". If the roof is so large that surface craters made by small or medium calibre bombs are not likely to cover an appreciable part of the total area, a normal working stress of perhaps 7 ton/sq.in. in the steel is, perhaps, permissible (note that since we are dealing here with static forces, it would be quite wrong to base calculations on the yield stress as in Chapter VII). If, however, for some reason, the roof is narrow and supported at its ends only, so that it forms a beam whose average depth might be decreased appreciably by a surface crater, a much lower working stress - say 4 ton/sq.in. - is desirable.

9.4 The attack by shaped charges

We have now to consider an entirely different form of explosive charge, which, although it explodes in air in close proximity to the target, is in no sense comparable with the ordinary shattering contact charge. It has been known for many years that a charge of cylindrical form having one end hollowed out into a conical cavity will produce results of unprecedented severity in the direction of the hollow end. Such charges, which are sometimes referred to as "Monroe" charges, have been developed for many purposes during the war. It has been found that their directional effect is much enhanced by lining the conical cavity with a metallic layer. When the charge explodes, this liner is ejected along the Axis of the cylinder at a very high speed, as a jet of liquid or gaseous metal. This jet is in effect a very high velocity projectile, and instead of shattering the concrete it bores a narrow hole, similar to that formed by an armour-piercing shot but much deeper. An 80 lb. shaped charge for example, is capable of forming a hole of 2 in. diameter clean through 10 ft. of reinforced concrete, and of producing a not inconsiderable blast effect locally on the far side.

* It is a curious feature that under these conditions the exposed bars may show several incipient "necks" like those produced just before fracture in a static tensile test.

These charges have not been used to any large extent in aerial bombing up to the present time but clearly they could be so used in at least two ways. Either a large number of charges could be dropped each of which would cause a small area of damage in the interior of the fortification, or a single larger charge might form a hole through which a smaller fragmentation or demolition bomb, originally placed behind the charge, might enter.

The very great penetrative powers of the shaped charge makes the "natural" method of defence - by increasing roof thicknesses - practically an impossibility; instead methods of defence based on the properties of the weapon itself must be contemplated. To produce its optimum effect, the charge must be offset, i.e. it must be fired a short distance (about one charge diameter) away from the surface attacked. If this surface is a perfectly plane one there is of course no difficulty in arranging this:- a false nose containing a rapid fuze can be provided in front of the explosive. If the roof is provided with a comparatively light "burster" placed some distance above the true roof, the explosion will take place in a position remote from that required for optimum performance. If the burster is inclined - for example, if it takes the form of an ordinary pitched roof - the situation may be still better, as not only is the fuze problem more difficult, but also the charge may be deflected from the normal before explosion, and thus forced to bore through a greater thickness of concrete before reaching the interior. Furthermore in these circumstances it is not unlikely that the "follow through" portion of the weapon, if it has one, will fail to find its way through the hole provided for it by the leading portion.

It is the common practice of the enemy to erect substantial pitched roofs over fortifications and large concrete shelters for camouflage or perhaps for aesthetic purposes. These roofs have not proved very effective, at least as far as camouflage is concerned, but it may well be that the further development of the shaped charge would make such measures a necessity.

9.3 Contact explosions in earth

Obviously, the confinement afforded by the earth, when a bomb explodes in contact with a concrete structure but below ground level, will greatly increase the forces to which the structure is subjected. Accordingly underground walls must be made heavier, if the same standard of resistance is required. Moreover, the shape effect is less important in earth, and the difference between "side-on" and "end-on" shots is much less marked.

In Table 9.3 we summarize the results of three full-scale experiments carried out to determine the critical thickness of concrete required to resist a side-on contact explosion in earth. These experiments were designed primarily to verify the dimensional theory under these conditions, and, although the method of support of the panels tested was not exactly scaled, it was found that over the small range of linear scales investigated there was no appreciable deviation from the theory. Comparison with small-scale tests, however, indicates that, as usual, the model work underestimates the damage slightly.

TABLE 9.3

CONTACT EXPLOSIONS ON CONCRETE - FULL-SCALE TESTS IN EARTH

Bomb	Charge-weight of Bomb (lb.)	Thickness of slab t(in.)	Reinforcement	Scabbing plate*	$t/W^{\frac{1}{3}}$	Damage
50 kg.S.C.[6] (side-on)	52	49	0.75 Two thirds near inner face One third near centre	No.	13	Wall partly shattered and bulged outwards by 0.5 span. Concrete cover on interior face scabbed off.
250 lb.AS[6] (side-on)	132	66	ditto	No.	13	Wall partly shattered and bowed 0.3 span. Concrete interior cover scabbed off, and projected across interior.
250 kg.S.C.[6] side-on	275	84	ditto	No.	13	Wall partly shattered and bowed 0.43 span**. Concrete interior cover scabbed off & projected across interior.

* In subsequent small-scale experiments, it was shown that scabbing plate placed within the interior layer of reinforcing (which was left bare,) prevented the discharge of concrete from the interior surface, but did not reduce the bulging of the panel as a whole.

** See overleaf.

The experiments listed in Table 9.3 indicate that a concrete wall, reinforced 0.75 per cent by volume of steel, with two-thirds of the reinforcing at the inner face, and subjected to the sideways-on contact explosion in earth of a bomb of charge-weight W lb. (TNT or amatol) will bulge a maximum distance equal to about half of the span if its thickness is given by $t/W^{\frac{1}{3}} = 13$. To reduce this deflection to our standard value 1/7th span, would require $t = 17W^{\frac{1}{3}}$. Experiments in the United States[7] have given a very similar result.

In the absence of a scabbing plate the concrete cover over the inside layer of reinforcement is detached and projected with some violence into the interior. The use of a steel lining is therefore as desirable here as when the explosion takes place in air.

9.6 The minimum thickness of floors

In the above paragraph we have been concerned mainly with the specification of the minimum thickness of an underground wall. The situation with regard to floors is somewhat different particularly if the fortification is small. (In a large building, capable of resisting penetration, an explosion under the floor cannot occur, except near the exterior walls from a bomb entering the ground obliquely, and so appropriate reductions of floor thickness in the interior can be made). An investigation of the position in which the explosion can take place in order to inflict a specified degree of damage on a floor of thickness $5W^{\frac{1}{3}}$ with the standard reinforcing has been made and its results are shown in Fig. 9.1. It should be noted that the ratio deflection/span used to define "heavy damage" is less than we have considered acceptable for walls. For a small "pill-box" of type investigated (about $48W^{\frac{1}{3}}$ in diameter; say 24 ft. across when the attack is by 500 lb. bomb) the decisive factor is not the damage to the floor itself but the fact that the whole structure is thrown into the air with velocity large enough to cause injuries in the interior whenever the explosion is within the volume indicated as causing "light damage". If the structure forms part of a larger unit, its velocity will of course be reduced but at the same time the local damage will become more severe, as the block movement of the whole is prevented. In Chapter XI we discuss in some detail the parallel problem of the effect of the movement of supports on the damage to a panel wall. All that need be said here is that whether the unit stands by itself, or forms part of a large structure, the reduction of the floor thickness to $5W^{\frac{1}{3}}$ can only be considered acceptable if the bomb is prevented from exploding in the area marked "light damage" in Fig. 9.1.

9.7 Geometrical considerations in design

In the preceding paragraphs we have laid down the fundamental dimensions of the fortification; we have showed that those portions of the exterior surface which are below ground level but are not inaccessible to contact explosions must be made far stronger than the above-ground portions, and we have stated that if the aim is to secure complete protection against a given size of missile, then the roof, and the above-ground portions of the walls must be approximately of the same thickness.

Our problem now is to examine the geometrical forms which can most achieve these standards most economically. Two generalizations can be made <u>a priori</u>

(i) A fortification of approximately cubical form will involve less expenditure of concrete per unit volume protected than (say) a flat structure of larger area.

(ii) Surface fortifications will be in general more economical than those partly or entirely sunk in the ground.

Several possible forms each intended for protection against the 500 lb. bomb are shown in Fig. 9.2[9]. In these forms, the above-ground wall thickness is somewhat below our recommendation, and the roof thickness somewhat above, because of the severity of damage resulting from a perforation when compared with even the closest near-miss. The floor thickness has been reduced to 36 in. (about $5W^{\frac{1}{3}}$) provided that the bomb cannot reach the "medium damage" zone as shown in Fig. 9.1 unless its path length in the soil exceeds 20 ft. In practice, it can be shown

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*** (see previous page)
In this test the edge support was inadequate and gave way somewhat; the total deflection at the centre of the wall was therefore greater than the bulge.

that even if the path length of the bomb in this material is 30 ft. the probability that its track will bring it into the danger zone is extremely small. In case 2, where a burster slab is used to prevent the bomb reaching the zone in which floor damage is to be expected, the thickness of this slab is taken as only $1\frac{1}{3}$ times the penetration of the bomb. Since the slab is earth-backed and not suspended, the effect of scabbing in increasing perforation will be less marked. For the same reason, little or no reinforcing is necessary in a burster. A further possibility is to place the burster vertically below the exterior wall as a "skirt" or "curtain" wall.[10] So placed, it is equally effective in preventing the bomb from reaching the floor-damage zone, and although it may be damaged by earth-shock from near-misses this damage is without importance since it does not affect the fortification itself.

9.8 Structural considerations in design

It will be quite clear that constructions of the type shown in the figure gain much of their strength from their continuity. Weaknesses at the junction of roof and walls, or of walls and floor, must be eliminated. It is essential that the concrete throughout the fortification should be as nearly as possible continuous and homogenous. In practice however construction joints between batches and pours are inevitable. A few principles can be laid down as to the way in which such joints should be sited.

(i) Joints should if possible run parallel to and not across the exterior surfaces, i.e., they should run horizontally in roofs, and floors; in walls vertically and parallel with the direction of the wall. All units should, however, be poured with the fewest possible number of joints. Not more than two or three lifts should be necessary in even the thickest roofs.

(ii) In roofs of very large area vertical joints may be essential both from considerations of thermal expansion and because the quantity of concrete required to pour a single lift over the whole area is beyond the capacity of the available plant. In these cases the vertical joints should be differently placed in the various lifts, so that no vertical joint runs through more than say one-third of the total thickness, and, if possible, all joints should be situated over division walls.

(iii) It may well be desirable to provide additional shear reinforcing at joints in the concrete, so that the shear strength at these points is as great as elsewhere.

It is also essential that reinforcement should be made as continuous as possible. This can best be done by welding successive lengths of bars together, or by hooking with an adequate overlap. Where the end of a bar is held by bond with concrete only, a lap length of not less than 72 diameters is recommended.

In prescribing continuity we must, however, make a clear distinction between those parts of the structure which are essential and those which are not. In Fig. 9.2 cases 1, 3 and 4, the structure forms a single unit, and everything must be done to ensure its continuity. In case 2 the structure itself is surrounded by a burster slab whose sole purpose is to prevent the bomb reaching a place in which it might damage the essential unit. It would be wrong under these conditions to make the burster continuous with the structure; it is quite true that to do so would decrease the damage to the burster slab, but only at the expense of increasing damage to the fortification itself. Damage to the burster is quite without importance and so the risk, however, small, that a continuous joint between burster and floor will increase the damage to the latter, should not be run.

A similar principle has been suggested for the design of fortifications in which one part has much greater importance than the remainder. As an

example of such a case we may quote the large gun emplacement, shown diagrammatically in Fig. 9.3. Here the vital item is the gun itself, but various magazines, stores, etc., are also necessary. The gun, on its large foundation slab is placed in the centre, and round it are constructed the "supply" shelters. A direct hit on the gun, capable of penetrating its overhead protection puts it out of action, but a direct hit on a magazine does not necessarily do so, since there are other magazines which may be drawn on. The surrounding structures must prevent penetration below or nearly below the foundation slab of the gun, as even a small movement of this slab will have fatal effects on the accuracy of fire. Finally, the displacement of the subsidiaries, resulting from a near miss must be prevented from causing any movement of the central slab. Clearly this is best done by permitting a completely free joint, or even a small air-gap between the central slab and the surrounding ring. Each unit - the gun, and the "supply" ring - must be as rigid, and as closely integrated as possible, but movement of the one relative to the other should not be retarded in any way.

9.9 Special technique during construction

We have already referred to the necessity for careful control of the pouring procedure during construction, the necessity for careful siting of joints, etc. Some other points arising from the very great thickness and weight of units are worthy of consideration.

(a) Placing of reinforcement. In fabricating a very thick slab, a mesh of reinforcement which may be 16 or 20 ft. thick must be laid beforehand, and must form a rigid framework, which will not distort awkwardly during pouring. The heavy reinforcement running through the thickness of the slab, which we have recommended as a precaution against scabbing, will be useful in imparting the necessary rigidity to this framework during erection. A system of reinforcing which has been very widely used, however, is the so-called "cubic mesh", which consists simply in three mutually perpendicular sets of bars of the same diameter, with the same spacing (usually 1 ft.) in each direction. This system is clearly not the most economical in steel, since it affords neither a concentration of bars on the inner face, nor a reduction near the outer face. On the other hand, it is of course, extremely simple in erection and this consideration has frequently outweighed that of economy when fortifications have had to be erected by unskilled or semi-skilled labour.

(b) Pouring of concrete. Given that reinforcement is placed at about one foot average spacing it is usually considered that aggregate size must be limited to a maximum of 2 inches*. Larger aggregates will give better resistance to penetration (for a given water-cement ratio) but difficulties of consolidation will generally preclude their use. Even with this limitation the problem of achieving a high density concrete when pouring through a 16 ft. thick mesh of steel bars is considerable, and necessitates the use of a much wetter mix than would be desirable on other grounds. Of course, when the concrete surface is accessible, ordinary methods of consolidation by vibration can be used, and thus near the upper face of a roof the large aggregate size and low water-cement ratio so desirable in resisting penetration can be introduced particularly if, as we recommend, the percentage reinforcement has been substantially reduced in this region. In principle, on the inside face of a slab, the reinforcing is the dominant factor, and the design of concrete must be adapted to suit the steel. On the outside face the converse is the case. We have here an additional argument for pouring a roof in horizontal layers rather than in vertical sections.

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* Of course, the presence of a very close reinforcing mesh on the inner face of a slab like that shown in Fig. 9.6 can be disregarded in selecting the maximum aggregate size. It is our deliberate intention that the aggregate should not pass through this mesh.

(c) The provision of the soffit or spalling plate. We have repeatedly argued in this chapter that all interior surfaces, with the possible exception of floors, should be given a steel lining. The practical engineering of this requirement can be approached in several ways. Two of the three here described are particularly adapted to roofs while the third is applicable mostly to walls.

(i) The "filler joist" method in roofs. This method consists simply in placing steel joists across the shorter span of the roof usually at about 1 - 3 ft. spacing, and filling the gaps between them with steel plate preferably welded to the lower flange, as shown in Fig. 9.4a. It is essential that the joists should be long enough to ensure that they will not pull off the supporting walls even when very badly bowed downwards. Their end anchorage can be improved by passing the vertical reinforcing bars in the supporting walls through holes drilled in the flanges, so as to ensure that the joist extends when bowed downward, and does not merely pull out of the concrete. If this is done it is permissible to include the steel in the joist in the computation of the percentage reinforcing in the lower layer of the roof, and thus to reduce somewhat the weight of steel in the body of the concrete, though this should not be allowed to fall below about 0.1 per cent, the minimum necessary to prevent widespread shattering. The steel in the scabbing plate itself, however, should not be included in this computation, since the roof can be deflected without appreciably extending it. The plate should not be less than 3/16 in. thick. Where possible joists should be made continuous over partition walls, and between successive portions of the building, though not, of course, where the free joints referred to above are required.

(ii) The "steel troughing" method in roofs. This method, illustrated diagrammatically in Fig. 9.4b, consists simply in covering the area of the roof with steel troughs placed across the shorter span and welded together. It is again essential that the troughs should be prevented from pulling off their end support, and accordingly wall reinforcement should be passed through holes drilled for the purpose. It is sometimes recommended that the bottom layer of steel in the roof concrete should also be either passed through the troughs or welded to them, in order to ensure bond between steel and concrete over the whole length. Since the steel only plays its real part when the concrete is already shattered as a result of spalling this measure may not be necessary.

Here again an allowance can be made for the weight of steel in the troughing in computing the percentage of reinforcement in the roof.

Both these methods have the advantage that they provide shuttering on the underside of the roof capable of sustaining a considerable load of concrete during pouring, and thus greatly simplifying the support of the roof during construction.

(iii) The plate-between-bars method in walls. It is clear that if methods (i) and (ii) are adopted both in roof and in walls difficulties may arise in securing an adequate anchorage at the joint for both sets of members: furthermore the strong shuttering afforded by these methods is not required on a vertical surface. For these reasons, the alternative shown in Fig. 9.4c has been evolved, and has proved satisfactory in an experiment. Here the steel spalling plate, which again must not be thinner than 3/16 in., is inserted between the horizontal and vertical bars of the inside reinforcing layer. The bars on the interior side of the plate, which of course are not in concrete at all should run across the shorter span of the wall. The usual precautions must be taken in

anchoring these bars. They may be hooked over horizontal bars in floor and roof, or bent to run horizontally for a length not less than 72 diameters, but it is essential that if the latter course is taken they should pass below the longitudinal reinforcing in the floor (or above that in the roof) so as to prevent them pulling out of the surface. In a multi-storey building, the vertical reinforcing should be made continuous in the whole height either by welding or hooking successive lengths together. The scabbing plate cannot usually be adequately tied at its edges, and so no allowance should be made for it in computing the percentage steel in the wall.

(iv) Other methods of retaining the scabbing plate. Various other devices have been suggested for retaining the soffit plate in position on the interior surface on the concrete. One such consists in passing ties round the reinforcing in the body of the concrete, and welding them to the surface of the plate. It has been suggested that these ties should be provided at a rate of 0.3 sq.in. per sq.ft. area. In the view of the writer such methods do not really afford an adequate solution of the problem. In at least one case they have been proved experimentally to be ineffective.

(d) The support of concrete during pouring. It will readily be appreciated that to pour a lift of perhaps 6 ft. in thickness over an area of roof having a minimum span perhaps 60 ft. at a height of 60 ft. above the ground, presents a considerable problem of structural engineering on its own account*. The ordinary methods of support with timber or steel shuttering are quite inadequate in such a case. Undoubtedly the best solution is to extend the principle noted above of carrying the concrete on the plate and joists which will ultimately form the bottom surface of the roof. To carry the tremendous load involved in this case on ordinary joists would, however, involve the use of unnecessarily large members, and accordingly each joist is replaced by a steel truss, of total depth usually about two-thirds of the roof thickness. In the case of a roof of total thickness 12 ft. to be poured in two equal lifts, the trusses might be placed at three foot centres, and have depth 8 ft. The central bending moment per truss for span 60 ft. after the first pour is 1.18×10^6 lb.-ft., so that the tension in lower member at the centre is 1.475×10^5 lb. It is unnecessary to provide for any "factor of safety" in the trusses, or even to keep within the elastic limit, since this load occurs once only, and for a short time while the concrete is hardening. A working stress of 10 tons/sq. in. is therefore quite acceptable, and accordingly joists of 10" x $4\frac{1}{2}$" x 25" are adequate. The top member of the joist must be laterally braced to prevent buckling, and the ordinary slab reinforcement can often be used for this purpose. The spalling plate, for which a light troughing can often be used to provide stiffness, is welded on to the lower flange of the bottom members in the usual way. In computing the percentage reinforcement required in the concrete, the steel in the lower members of the trusses can be taken into account, but not the remainder since it is very badly placed for most purposes. The first lift of concrete must of course be allowed to harden before the second is poured, and the whole reinforcing system must be more than sufficient to sustain the final static load due to the weight of the slab.

In some cases in fortifications having the lower surface of the roof at or near ground level, a heroic expedient has been adopted. The walls are first constructed in trenches of appropriate dimensions dug for the purpose. The lower-face steel and roof reinforcing are then placed in position and the whole roof is cast on the ground. After an appropriate interval to allow for hardening of concrete, the earth is then

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* This was approximately the problem which faced the enemy during the construction of the Atlantic coast submarine pens.

excavated from under the roof slab, and finally when excavation has proceeded to the specified depth, the floor is placed in position. The floor in this type of structure is usually a light one, and floor damage is prevented by a burster slab forming an extension of the main roof. Where a semi-sunk or fully sunk construction is required, this method has much to recommend it, and, indeed, its simplicity is an argument in favour of the selection of semi-sunk forms of construction where a very high degree of protection with corresponding enormously heavy roofs is required. Of course, the condition of the site is always a dominating factor in such designs. The soil may be too hard to permit large-scale excavation, or alternatively too waterlogged to allow sunken construction.

(e) The repair of bomb-proof structures. Any structure, even the most massive is liable to bomb damage of more or less severity. If the design is completely successful, and the weapons used are no more powerful than those contemplated by the designer the damage will be restricted, in the case of direct hits, to surface craters with perhaps some slight bulging in the steel-work on the underside of the roof at the point struck, and in the case of a near miss, to cracking in the concrete in the walls with some bulging of the inner surface. In such cases an effective repair can be carried out simply by patching the exterior face with plain concrete.* If there is no bulging on the inside face such a repair will practically restore the original strength. If some bulging has taken place, the status quo cannot quite be restored, but a compensating strength can be achieved by increasing the thickness over the damage span with an additional layer of concrete. If the original static strength (in the case of a roof) was insufficient to sustain the additional weight, then additional support must be provided in the interior in the manner described below.

If severe damage has been done, if the roof or walls are holed or very badly bulged, it must be assumed (indeed it will probably be obvious) that some of the inner-face steelwork has been effectively destroyed. To restore it exactly will necessitate cutting out the original members - a lengthy operation if they are, as they should be, well embedded in concrete at their ends. A much easier method is simply to cut away the loose ends of the original inner-face steelwork, and erect a new frame consisting of steel members supported at their ends either on concrete posts, or on continuous steel stanchions. Having thus provided the necessary support on the inside face, the hole or bulge can be patched with concrete on the outside as before. If an open hole is being repaired, it can be seen whether the reinforcing bars in the interior of the concrete have or have not been cut. If they have, the loose ends can be straightened and welded together to provide the necessary reinforcement for the new concrete. If they are still intact, the fact that they are somewhat distorted is probably of no consequence. When the bomb has not blown an open hole, but has caused a severe bulge, it can usually be assumed that the reinforcing bars in the solid have not been cut, unless the concrete is so badly shattered that it can easily be removed, leaving an open hole.

We have now touched on most of the main points which arise in the design of heavy shelters and fortifications. We devote the few pages remaining in the chapter to more detailed consideration of three individual designs, differing widely in size and strength.

9.10 Commentary on three existing designs

(a) The original "bomb-resisting" shelter [11] One of the original "bomb-resisting" shelters designed in 1939 is shown in Figs. 9.5a and 9.5b. At this time practically none of the experimental work described in this book had been carried out, and the designers had only the most fragmentary information on which to proceed. How would more modern information modify their plan ?

First, with regard to the dimensions of the structure as a whole, it will be noticed that the roof thickness exceeds that of the walls above ground level. That is to say, the roof would only be perforated by a bomb larger than that which, exploding sideways-on in contact would blow a hole in the walls. This, of course, is a perfectly logical and correct design. Not only is the chance of a direct hit much larger than the chance of a near-miss so exactly placed as to give the effect of sideways-on contact, but the consequences of perforation are far more serious than those of any external explosion, even one capable of blowing a hole in the wall. In the former

* Loose pieces of concrete must be removed from the crater before the new patch is poured.

case all the occupants of the shelter will be exposed to severe risk, in the latter case only those near the hole, who are likely to be struck by flying pieces of concrete, are in much danger. Three out of the four compartments will probably be safe. Thus it is the perforation that must be countered as a first priority. The wall thickness below ground level is made consistent with that above ground level; again a quite sound procedure, although the probability of an effective contact shot is perhaps a little higher than above the surface since the attitude of the bomb is less important. When they came to the floor, however, the designers did not continue with the policy of providing less protection against unlikely events than against probable ones. They realized that for equal resistance to explosion, floor and sub-surface walls must be equally thick and they designed accordingly. But a contact shot below the floor is definitely more improbable than one against the walls, and so a logical policy would reduce the thickness there. Probably a modern design would show a floor thickness reduced to about 3 ft. 6 in. The increased wall thickness required below the surface would probably be placed outside rather than inside the above-ground walls in order to secure increased internal volume with only a small additional consumption of material.

When we come to the reinforcing diagram, Fig. 9.5b, we see that ideas have changed rather fundamentally. Except for some additions on the underside of the roof, the steel is roughly uniformly distributed between inner and outer faces, whereas the contemporary plan is to place the greater part of the steel on the inside, most of the remainder near the centre, and almost none at the outside. The idea of scabbing plates for walls, as well as roof is comparatively recent, and we have already stated that we consider the means adopted here for anchoring the roof scabbing plate (by vertical links) to be inadequate.

(b) A German "Bunker" shelter[12] In Fig. 9.6a is shown a plan and section of one of the large "Bunker" shelters built by the Germans in the years 1941-43. The one shown is one of the most recent, and was in fact left unfinished in 1944. The idea that roof and above-ground walls should be of the same thickness, has been adopted, though, as we saw above, it is very questionable whether this arrangement is in fact the best. The intention has apparently been to provide complete protection against the 1000 lb. bomb, and to neglect the risk that a larger penetrating bomb might be used, and it is arguable that the policy was justified by events - very few delay-fuzed bombs larger than 1000 lb. were in fact dropped on Germany.

A much more serious error has however been made in the internal design of the shelter. Only the roof, walls and outside wall footings have been reinforced. Internal walls have been constructed of mass concrete or brick. Even a quite small internal explosion, or a large external explosion near the door might be sufficient not only to demolish such walls, but to convert them into most dangerous missiles which could not fail to cause many casualties. The percentage reinforcing necessary to prevent this disintegration is as we have seen very small, not more than 0.06 per cent, but its presence is essential in almost all construction for protective purposes.

In Fig. 9.6b we show the wall reinforcing arrangement which we have already instanced as being one of the best that has been devised. True, the writer would prefer to omit the concrete cover on the inside face, and to replace the close mesh of small bars shown in the diagram by continuous strips of sheet steel passed through the large U-frames, with narrower pieces welded on to close the gaps between frames. It may seem that this change is difficult to carry out, and that it does not provide any large increment in safety. The reply may be made that since the arrangement avoids the use of internal shuttering it will not on balance lead to an increase of labour requirement. Further, we may remark that a piece of the internal cover concrete, say 1 ft. square and 2 in. thick weighing 2 lb. does not have to travel very fast to cause a serious injury.

(c) A typical "very heavy" fortification[13] Fig. 9.7 shows the immense concrete fortification constructed by the Germans at Siracourt in the Pas de Calais. This erection was of course cast on the ground, and the subsequent excavations were never completed. Its general shape was presumably laid down from considerations of the purpose for which it was required; apparently a chamber about 14 ft. high 50 ft. wide and 600 ft. long with a single large entry had to be made as nearly as possible bomb-proof*.

For this purpose, the general shape of the section can hardly be improved on. The burster and the short wedge-shaped walls make it very unlikely that a bomb will ever penetrate below the floor. The roof is, nominally at least, proof against the largest bomb at that time in our armoury - the 12,000 lb. M.C. known as "Tallboy". The transverse roof reinforcing was much as we have recommended, and there was a soffit plate supported on rolled steel joists in the manner of Fig. 9.4a. Yet this structure was attacked and so seriously damaged that the whole project was abandoned.

The roof plan in the diagram shows how this happened. The designer had made two errors, one slight, the other serious, and, with remarkable consistency, the two bombs shown on the plan exploited these errors to cause damage, one slight and the other serious. Let us consider first the near-miss shown on the top edge of the plan. This near-miss destroyed a length of burster, but this was of course, of no consequence, since the burster is there for that purpose. The designer had realized that it was necessary to use a "unit construction" to make a joint between the burster and the main structure which would enable the former to move freely without damaging the latter. Instead of carrying out this plan logically however, he allowed the roof to lap a few feet over the burster, as shown in the section, and thus he prevented free relative movement. The near-miss bomb, therefore not only broke up the burster slab but also caused a complicated system of cracks to spread through the main roof from the point where the burster lifted it. The error here was slight - a mere matter of stepping the joint between roof and burster instead of leaving it plain, and the damage also was not very serious.

In designing the roof slab, however, undue attention was given to the problem of contraction. Every few yards along the length of the building there was a completely discontinuous butt joint through which no reinforcing bars were passed, and in which a layer of precast blocks were placed, presumably with a view to allowing free relative movement of adjacent sections. The direct hit indicated on the plan fell exactly on one such joint, penetrated some distance and in its explosion caused very serious damage, which if the excavation had been complete at the point, would probably have amounted to collapse, over the two portions of the roof between which it struck. Had longitudinal continuity been maintained, the damage would have been much less severe both because the absence of the joint would have reduced the penetration of the bomb and because the damaged portions would have received much greater support from their neighbours. True, some slight damage might have been transmitted to these adjacent portions had the roof been continuous. But for the proper working of the building it was essential that the whole length should be intact. To adopt a construction which made it easy to put the whole out of action by destroying a single section was therefore, as the event proved, totally incorrect.

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* There is reason to believe that the designer had especially in mind attack by the British 2000 lb. armour-piercing bomb. He was not informed as to the development of a larger missile - Tallboy.

TABLE 9.1

CONTACT EXPLOSIONS ON CONCRETE - FULL-SCALE TESTS IN AIR

Bomb	Charge-weight of bomb W lb.	Thickness of slab t (in.)	Reinforcement	Scabbing plate	$t/W^{\frac{1}{3}}$	Damage
50 kg. S.C.4 (side-on)	55 TNT	24	0.7% two-thirds within 1 ft. of inner face	No	6.3	Slab completely perforated, forming hole 3 ft. in diameter.
500 kg. S.C.5 (side-on)	500 lb. (Approx.) TNT	72	1% two-thirds within 1 ft. of inner face	Yes	9.1	Surface crater 11 ft. diam. x 2 ft. in deep concrete through the whole thickness, shattered, but retained on reinforcing in rear surface. Bulge at rear 31 in. on a clear span of 18 ft. Soffit plate displaced.
50 kg. S.C.5 (side-on)	55 lb. TNT	39	0.38% two-thirds near inner face	No	10.2	Surface crater 4 ft. diam. x 9 in. deep. Concrete on the rear face behind inner reinforcing layer scabbed off over area 9 ft. x 6 ft. Permanent deflection of reinforcing 3 in. on 6 ft. span.
Bomb replica4 (cased charge) side-on	$1\frac{3}{4}$ oz. PE *	3	0.66% five-eighths near inner face	No	6.3	Slab completely perforated, forming hole 5" in diameter.
Bomb replica4 (cased charge) side-on	$1\frac{3}{4}$ oz. PE	$3\frac{3}{4}$	0.53% five-eighths near inner face	No	7.8	Surface crater 6 in. diameter x 1 in. deep. Very heavy scabbing at rear. The rear reinforcing failed to retain the shattered concrete in a volume 5" diameter x 2" deep, and a much larger area was shattered, but retained.
Bomb replica4 (cased charge) side-on	$1\frac{3}{4}$ oz. PE	$4\frac{1}{8}$	0.49% five-eighths near inner face	No	8.6	Surface crater 6 in. diameter x 1 in. deep. Very heavy scabbing at rear. Rear reinforcing failed to retain concrete in a volume 3" diameter x 1" deep, and a much larger area was shattered, but retained.

* For a note on the use of this explosive in small-scale tests, see Chapter VI.

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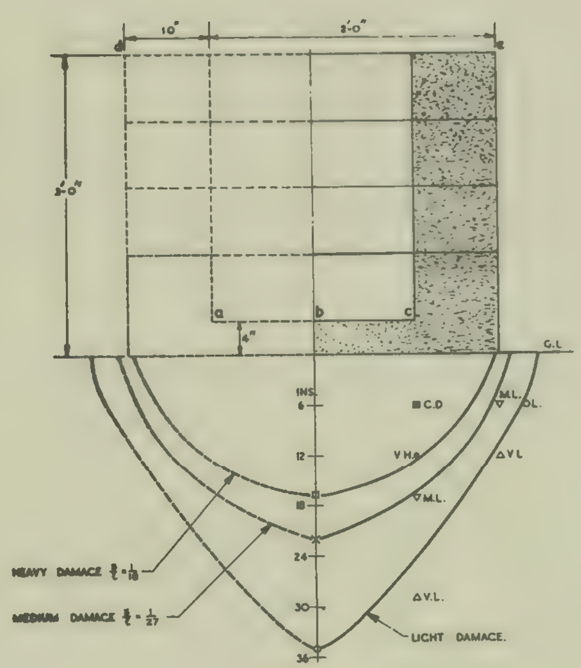
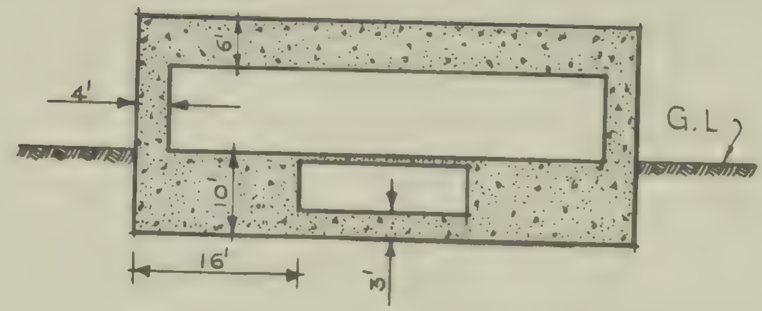
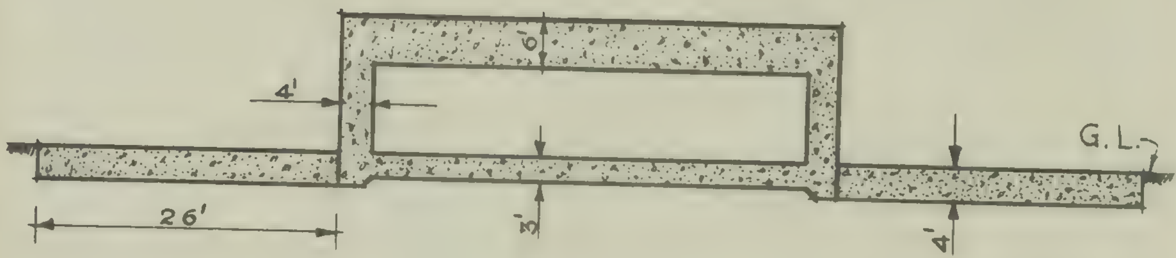


C.D. COMPLETE DESTRUCTION ■
V.H. VERY HEAVY ●
H. HEAVY □
M. MEDIUM ×
M.L. MEDIUM-LIGHT ▽
L. LIGHT ○
V.L. VERY LIGHT △

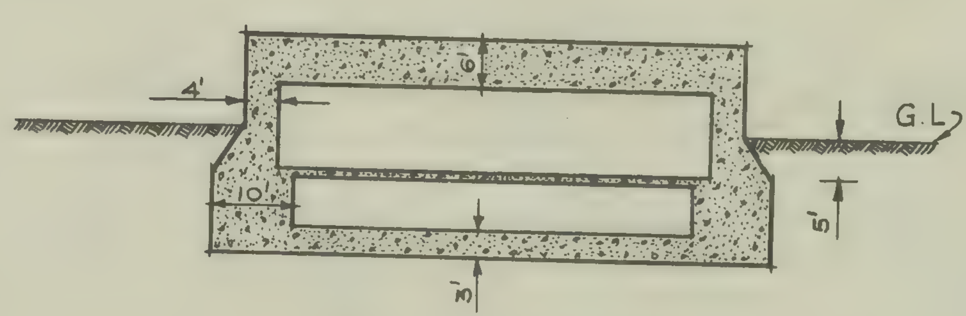
FIG 9·1 ZONES OF DAMAGE



Case 1 (Surface)

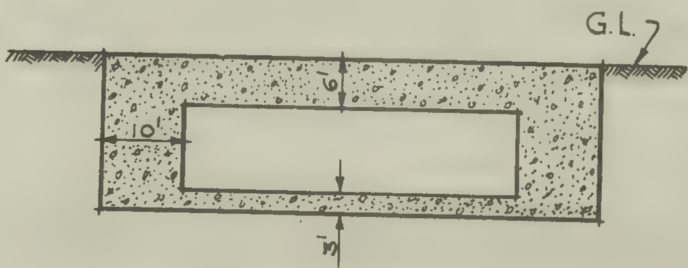


Case 2 (Surface)



Case 3 (Semi-sunk)

Note:- All dimensions are in feet.



Case 4. (Sunk).

Diagrams of Shelters

Fig: 9.2

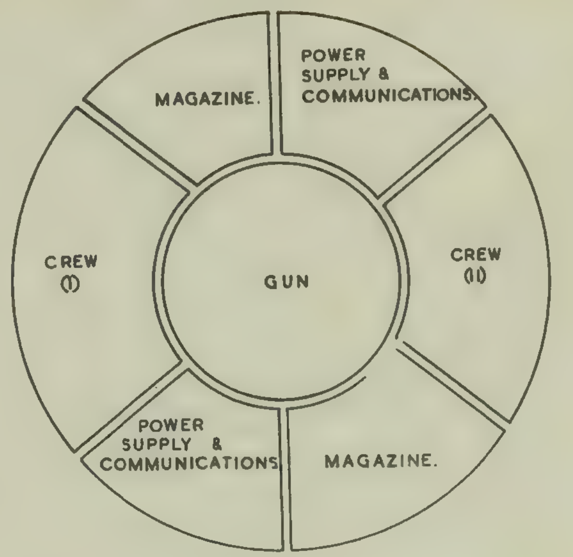


FIG. 9.3.

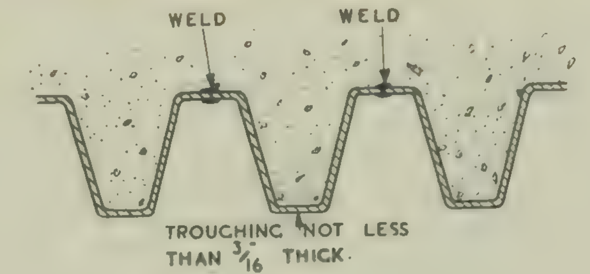


FIG.9. 4. b.

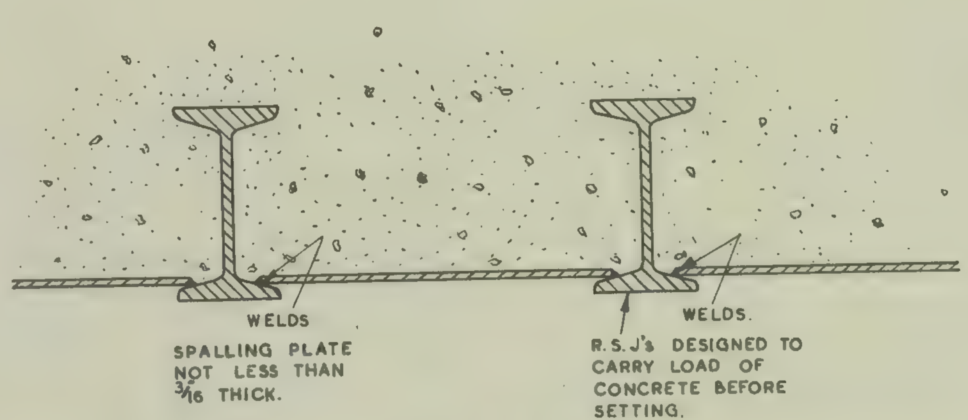


FIG. 9.4. a.

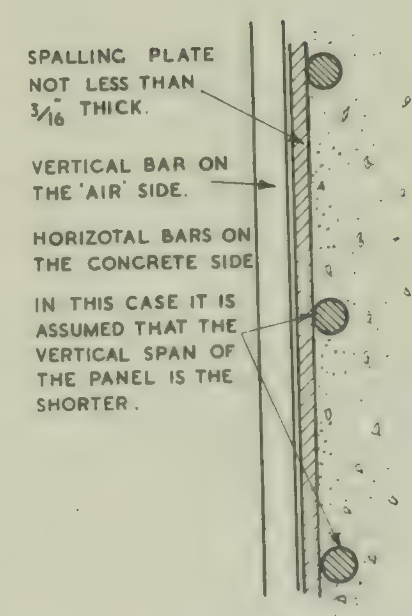


FIG.9. 4. c.

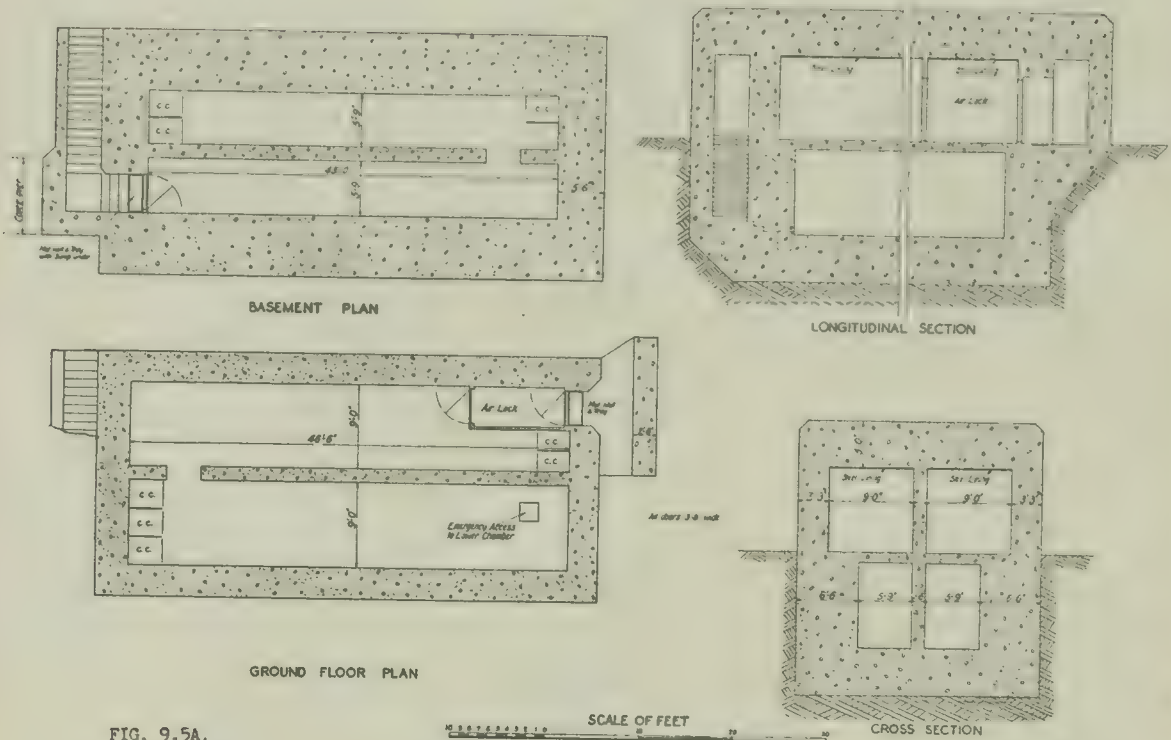


FIG. 9.5A.

RECTANGULAR SHELTER FOR 200 PERSONS

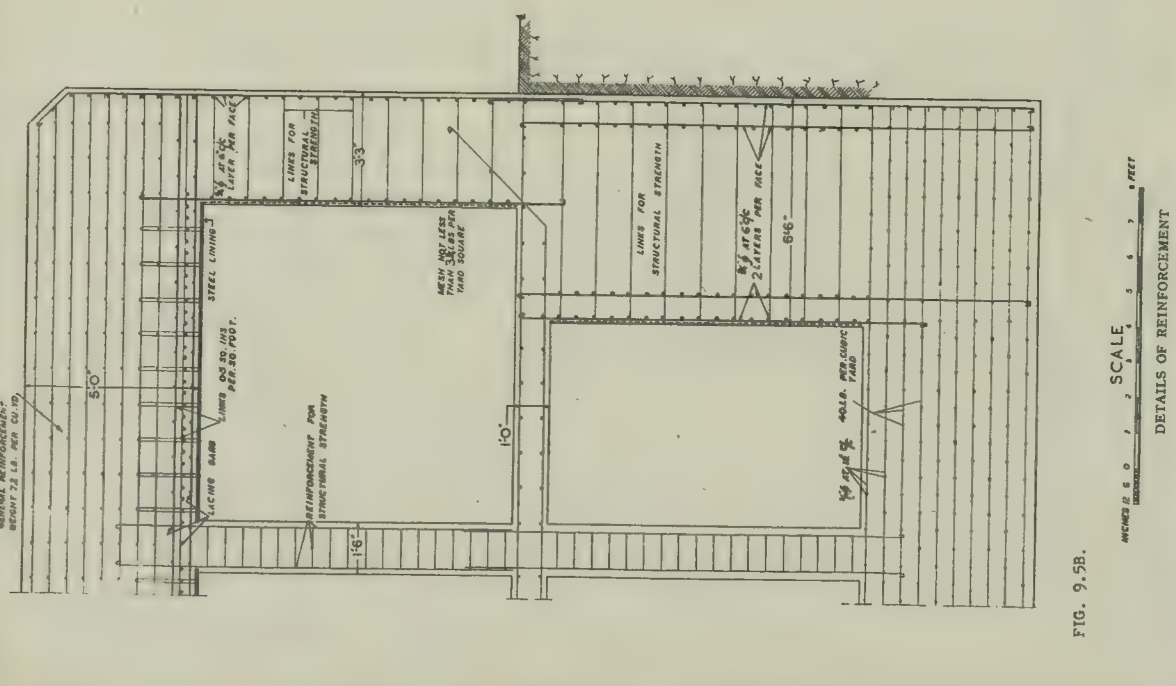
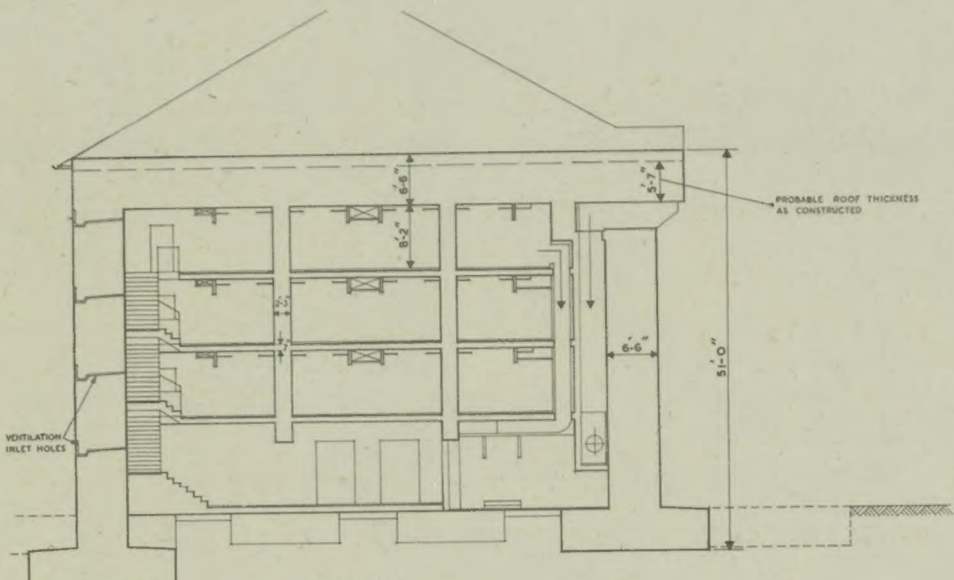
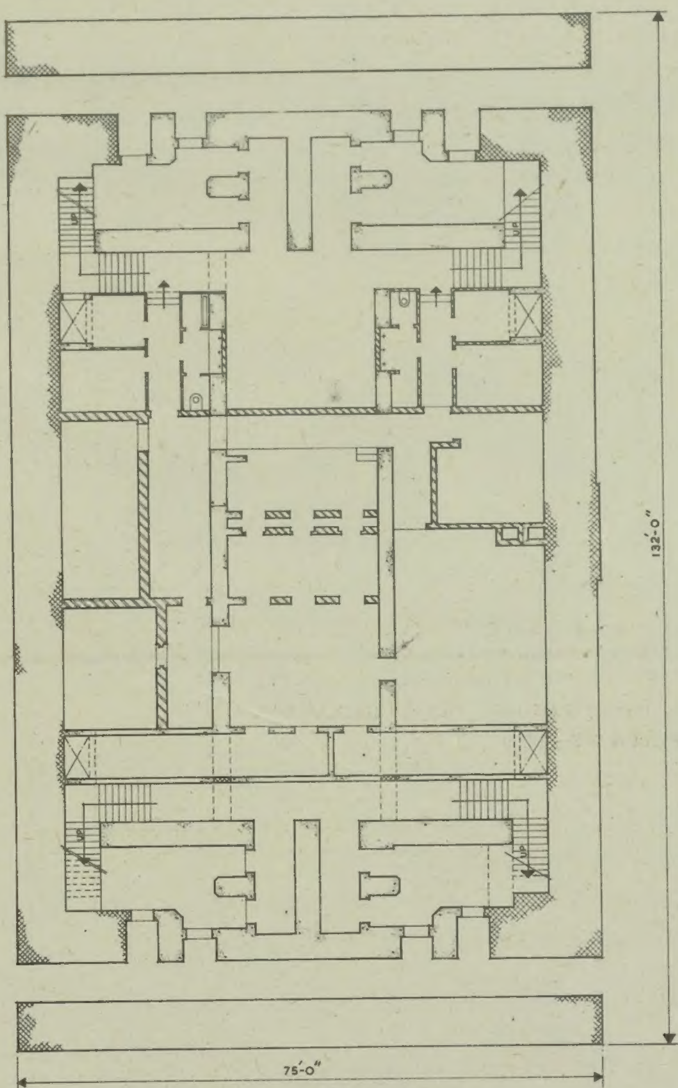


FIG. 9.5B.

DETAILS OF REINFORCEMENT



· SECTION ·



· PLAN ·

BRICKWORK
MASS CONCRETE
REINFORCED CONCRETE

2 0 2 4 6 8 10 20 30
SCALE OF FEET

FIG. 9.6a
AACHEN.
HOHENZOLLERNPLATZ.
SHELTER No. 20.

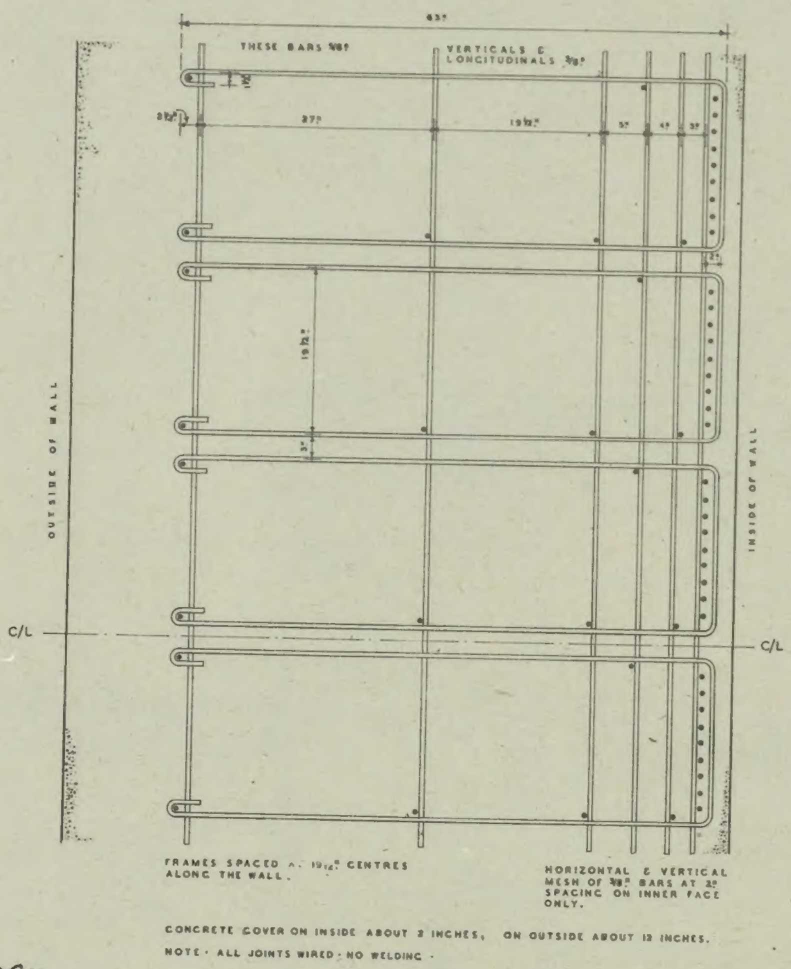


FIG. 96b · WALL REINFORCING · HOHENZOLLERNPLATZ · (SHELTER NO. 20.)

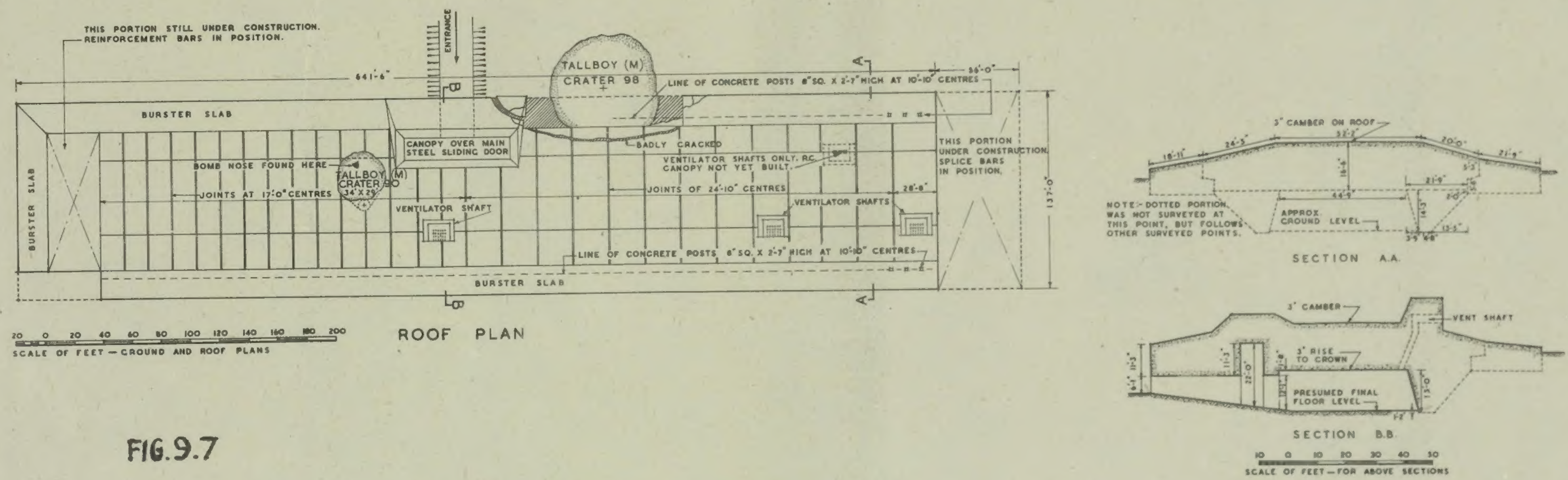

THIS PORTION STILL UNDER CONSTRUCTION. REINFORCEMENT BARS IN POSITION.
ENTRANCE
TALLBOY (M) CRATER 98
641'-6"
LINE OF CONCRETE POSTS 8" SQ. X 2'-7" HIGH AT 10'-10" CENTRES
56'-0"
BURSTER SLAB
CANOPY OVER MAIN STEEL SLIDING DOOR
BADLY CRACKED
VENTILATOR SHAFTS ONLY. R.C. CANOPY NOT YET BUILT.
THIS PORTION UNDER CONSTRUCTION. SPLICE BARS IN POSITION.
BOMB NOSE FOUND HERE
TALLBOY (M) CRATER 50 34'X29'
JOINTS AT 17'-0" CENTRES
JOINTS OF 24'-10" CENTRES
VENTILATOR SHAFTS
28'-8"
VENTILATOR SHAFT
137'-0"
LINE OF CONCRETE POSTS 8" SQ. X 2'-7" HIGH AT 10'-10" CENTRES
BURSTER SLAB
ROOF PLAN
SCALE OF FEET — GROUND AND ROOF PLANS
3' CAMBER ON ROOF
NOTE:- DOTTED PORTION WAS NOT SURVEYED AT THIS POINT, BUT FOLLOWS OTHER SURVEYED POINTS.
APPROX. GROUND LEVEL
SECTION A.A.
3' CAMBER
VENT SHAFT
3' RISE TO CROWN
PRESUMED FINAL FLOOR LEVEL
SECTION B.B.
SCALE OF FEET — FOR ABOVE SECTIONS

FIG. 9.7

CD.807.

R.C. 450

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MINISTRY OF HOME SECURITY

RESEARCH AND EXPERIMENTS DEPARTMENT

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January, 1946.